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# MONTHLY WEATHER REVIEW

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## PYRHELIOMETER CALIBRATION PROGRAM OF THE U. S. WEATHER BUREAU

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### ABSTRACT

A new system developed for calibrating the horizontal incidence pyrheliometer is described. The pyrheliometers to be calibrated are exposed simultaneously with a standard pyrheliometer in an integrating sphere. Calibrations are made by comparing voltages developed by the instruments undergoing calibration with those of the standard pyrheliometer. Calibration of the standard pyrheliometer is based on comparisons with the Smithsonian Institution pyranometer, both out-of-doors on clear days and within the integrating sphere. Advantages of the new system include reproducibility of the calibration within less than one percent. This is due to the reproducibility of the radiation field in the integrating sphere, in which there are relatively small variations in ambient temperature. The calibrations can be done much more rapidly and accurately than was formerly the case when the work was done out-of-doors; clear skies and minimum atmospheric pollution were necessary conditions previously.

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### INTRODUCTION

The purpose of this paper is to describe a new system of calibrating the horizontal surface pyrheliometer. In order to show the historical continuity of the radiation

activities of the Weather Bureau, a description and analysis of the previous calibration procedures are given.

For some time prior to 1952 the need for improvement in the procedures for calibration of the horizontal surface pyrheliometer was becoming acute as the radiation network expanded. In the summer of that year the Instrument Division and Scientific Services Division of the Bureau reviewed the calibration procedures then in use, with the object of improving them before beginning a recalibration program for all Weather Bureau horizontal surface pyrheliometers.

The horizontal surface pyrheliometer used by the Weather Bureau, originally designed by Kimball and Hobbs [1] and now universally known as the Eppley pyrheliometer after the manufacturer, has been calibrated in the past by indirect reference to the Smithsonian water-flow normal-incidence pyrheliometer [2].

### OLD CALIBRATION SYSTEM

#### LINKAGE OF CALIBRATION OF FIELD PYRHELIOMETERS TO WATER-FLOW PYRHELIOMETERS

The old calibration process involved a series of steps as follows:

1. By the Smithsonian Institution: (a) Absolute cali-

bration of the water-flow normal-incidence pyrheliometer [2]. (b) Calibration of the Smithsonian Institution silver-disk pyrheliometer by direct comparison with the water-flow pyrheliometer [3, 4, 5].

2. By the Smithsonian Institution and Weather Bureau jointly: Calibration of a Weather Bureau silver-disk pyrheliometer against the Smithsonian Institution silver-disk pyrheliometer.
3. By the Weather Bureau: Calibration [6] of a standard Eppley horizontal surface pyrheliometer against the Weather Bureau silver-disk, for use by the manufacturer of the Eppley in calibration of pyrheliometers.
4. By the manufacturer: Calibration of the instruments used by the Weather Bureau in its field network, by comparison with the standard horizontal surface Eppley calibrated by the Weather Bureau for that purpose.

#### ERROR SOURCES

In order to determine how best to improve the calibration process, the precision of the above steps was examined. The essential facts are: The water-flow pyrheliometer of the Smithsonian Institution has long been the fundamental standard of pyrheliometry in the United States, and seems to be regarded generally as being at least as good as any other existing instrument for the measurement of flux density at normal incidence to the sun. In several European countries the standard of pyrheliometry is the Ångström pyrheliometer, an instrument based on physical principles different from those of the water-flow. Comparisons have been made indirectly between the two standards. The results indicate that the standards are in close agreement. Ångström [7] indicates that the two can be reconciled within 0.1 percent. No further examination of the water-flow will be made here. The question of "pyrheliometric scale" is treated in a final paragraph.

Calibration of the Smithsonian silver-disk pyrheliometer against the water-flow is reproducible with an accuracy of the order of a tenth of 1 percent. Data are shown in table 1, the source being page 7 of [5].

Calibration of the Weather Bureau silver-disk No. 1 against the Smithsonian silver-disk pyrheliometer (No. A. P. O. 8 bis) is of the same order of accuracy as that of the Smithsonian silver-disk against the water-flow—about one-tenth of 1 percent. Data kindly supplied by Mr. Aldrich of the Smithsonian Institution are shown in table 2.

TABLE 1.—A summary of all comparisons between S. I. 5 bis and standard water-flow pyrheliometer No. 5. (Source: p. 7 of [5])

No. of values	Date	Mean constant
37.....	1932.....	0.3625
42.....	1934.....	.3629
18.....	1947.....	.3626
100.....	1952.....	.3622
Mean.....		.36255

Average deviation from mean  $\pm 0.055$  percent.

TABLE 2.—Calibration of Weather Bureau silver-disk pyrheliometer No. 1 against Smithsonian Institution silver-disk pyrheliometer A. P. O. 8 bis. (Source: data supplied by Mr. Lyle B. Aldrich of the Smithsonian Institution.)

No. of values	Date	Mean constant
8.....	June 3, 1930.....	0.3714
8.....	April 20, 1931.....	.3700
8.....	April 4, 1932.....	.3703
8.....	March 15, 1934.....	.3704
17.....	September 25 and 26, 1936.....	.3717
16.....	October 23, 1940*.....	.3720
11.....	January 8, 1942.....	.3721
24.....	April 27, 1945.....	.3743
24.....	October 16, 1948.....	.3729

\*In October 1940 new mercury was inserted in S. I. 1 and the silver disk reblacked.

TABLE 3.—Extreme variation about its mean calibration for each of a set of standard Eppley pyrheliometers. (Source of basic data: Mr. Hedley Greer of Eppley Laboratories.)

Standard Eppley pyrheliometer no.	Difference between extreme calibrations as a percent of the mean
395.....	7
389.....	7
245.....	8
362.....	4
489.....	5
1822.....	4

The standard Eppley pyrheliometer is calibrated against the Weather Bureau silver-disk as described in [6]. Some information on the accuracy of the results of this process is obtainable indirectly from an analysis of the calibration constants obtained over a period of years for the standard pyrheliometers. Data for six instruments indicate an average deviation about the mean of  $\pm 2$  percent. Extreme variations (highest value minus lowest value divided by the mean of the constant of the individual instrument) for each of six pyrheliometers are shown in table 3. Time series graphs of the constants of five pyrheliometers are shown in figure 1. (Data on which this figure is based were kindly provided by Eppley Laboratories, Inc.)

It was originally assumed that variations in the constant of a pyrheliometer with time arose from substantial changes in the instrument. However, in view of the apparent random nature of the variations shown in figure 1, it appears that such an assumption is questionable, and that the changes may well have been associated with circumstances of the calibration process, such as ambient temperature, rather than with actual changes in the pyrheliometers.

It is difficult to obtain data on the error involved in calibration of the instruments actually used in the field against the standard pyrheliometer. For example, data showing calibration of one pyrheliometer against a particular standard over a series of years are not available. We are forced to consider indirect evidence.

Calibration constants for a set of 12 pyrheliometers called in from the field for recalibration and calibrated originally by the manufacturer against the same standard Eppley (the calibration constant of which had remained unchanged during the period of calibration of the 12 field

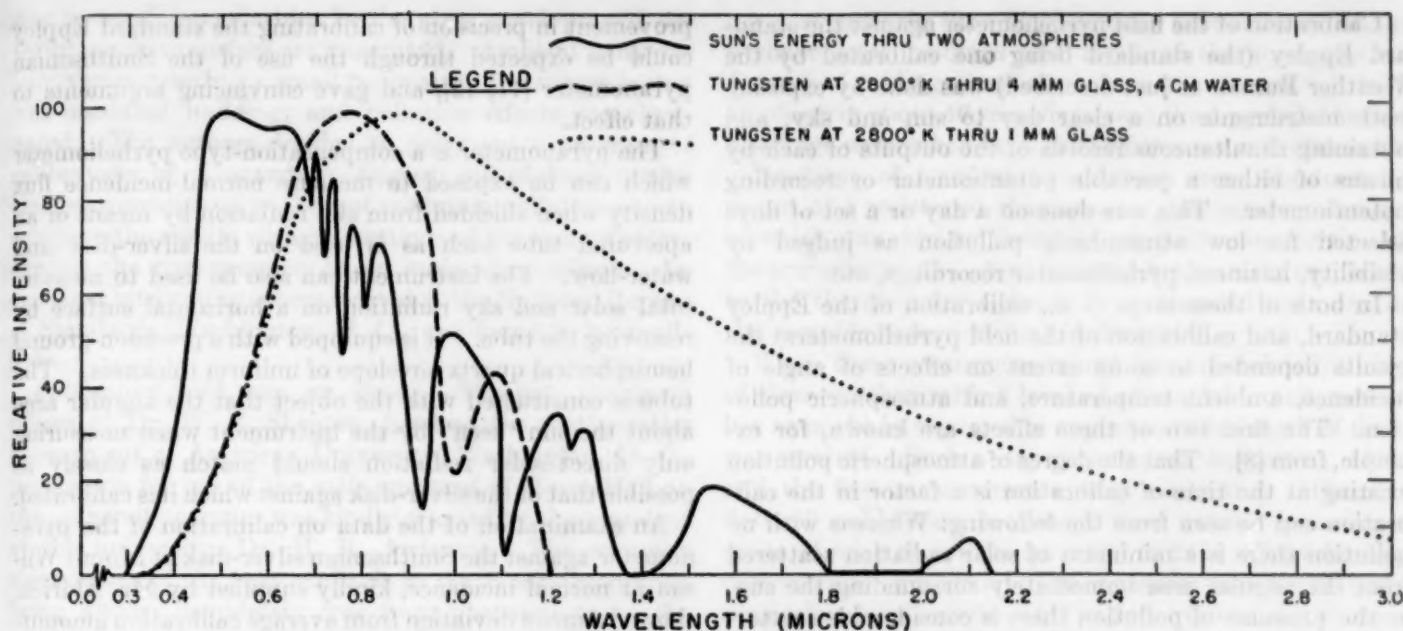


FIGURE 1.—Time series of calibration constants of five standard pyrheliometers. (Data from Eppley Laboratories, Inc.)

TABLE 4.—Comparison of original calibration constants with laboratory constants

Pyrheliometer serial No.	Original calibration constant	Integrating sphere calibration constant (c. c.)	Fractional deviation of original c. c.	"Random Error"*
1674.....	2.13	2.12	-0.00	+0.043
1689.....	2.07	2.13	-0.03	+0.013
1693.....	2.09	2.14	-0.02	+0.023
1719.....	2.29	2.44	-0.06	-0.017
1720.....	2.30	2.34	-0.06	-0.017
1759.....	2.34	2.53	-0.07	-0.027
1772.....	2.37	2.57	-0.08	-0.037
1793.....	2.38	2.48	-0.04	+0.003
1799.....	2.45	2.41	+0.02	+0.063
1805.....	2.23	2.35	-0.06	-0.017
2273.....	2.40	2.57	-0.07	-0.027
Mean.....			-0.043	.000
Mean of absolute value.....				.026

\*The "random error" is here obtained by adding 0.043 to the individual values in the preceding column. -0.043 is the mean of the fractional deviations.

TABLE 5.—Uncertainty in the steps of the old calibration system

Step	Method of determining degree of uncertainty	Approximate uncertainty percent
Calibration of water-flow.....	Indirect comparison with European standard.	0.1
Smithsonian silver-disk vs. water-flow.....	Average deviation about mean calibration.	.055
Weather Bureau silver-disk vs. Smithsonian silver-disk.....	do.....	0.1
Standard Eppley vs. Weather Bureau silver-disk.....	do.....	2
Field instruments vs. standard Eppley.....	do.....	4

pyrheliometers) can be compared with the calibrations recently obtained for the same set of instruments under laboratory conditions to be described. Results are shown in table 4. These data indicate that the original calibrations of the set were systematically about 4 percent low, and that there was a random component of error amounting to about 3 percent. (If the calibration constant is too low, indicated radiation is too high.)

The information outlined above is summarized in table 5. No precise or elaborate statistical treatment is needed to show the relative importance of the several error sources in the calibration chain connecting the water-flow standard to calibration of the Eppley pyrheliometers used in our field network. The brief examination above indicates clearly that improvement in the process should begin with the calibration of the standard Eppley, and should include calibration of the field pyrheliometers against the standard Eppley.

#### DETAILS OF OLD METHOD OF CALIBRATING EPPLEY STANDARD AND FIELD PYRHELIOMETERS

In the old calibration process, the standard Eppley (which measures flux density  $Q$  on a horizontal surface from the entire hemisphere of the sky) was calibrated against the Weather Bureau silver-disk (which measures flux density  $N$  from the sun, on a surface normal to the sun's direction). We designate the e. m. f. generated by the Eppley in measuring  $Q$  as  $e_q$ . The Eppley can also be used to measure the diffuse sky radiation flux density  $D$  on a horizontal surface by shading the pyrheliometer from the direct sun by means of a shade-ring or disk [6]. The e. m. f. of the Eppley when measuring  $D$  will be written  $e_d$ .

Calibration of the Eppley against the silver-disk is done by recording  $e_q$  and  $e_d$  alternately over a short time interval during which  $N$  is also measured, during a day having cloudless skies. The calibration constant  $C$ , in millivolts/langleys\* per minute, is computed from

$$C = \frac{(e_q - e_d) / \cos i}{N}$$

where  $i$  is angle of incidence.

\*One langley is 1 gram calorie per square centimeter.

Calibration of the field pyrhelimeter against the standard Eppler (the standard being one calibrated by the Weather Bureau as just described) was done by exposing both instruments on a clear day to sun and sky, and obtaining simultaneous records of the outputs of each by means of either a portable potentiometer or recording potentiometer. This was done on a day or a set of days selected for low atmospheric pollution as judged by visibility, haziness, pyrhelimeter recordings, etc.

In both of these steps (i. e., calibration of the Eppler standard, and calibration of the field pyrhelimeters) the results depended to some extent on effects of angle of incidence, ambient temperature, and atmospheric pollution. The first two of these effects are known, for example, from [8]. That the degree of atmospheric pollution existing at the time of calibration is a factor in the calibration can be seen from the following: Whereas with no pollution there is a minimum of solar radiation scattered from the angular area immediately surrounding the sun, in the presence of pollution there is considerable scattering. Further, the intensity of this scattered radiation varies markedly with angular distance from the sun. Therefore, under conditions of pollution the degree to which the silver-disk "sees" the same flux as the horizontal-surface pyrhelimeter being calibrated depends on the precision with which the angular area presented by the shade ring or disk matches the angular area irradiating the silver-disk pyrhelimeter. Also, with pollution, the geometry of the normal-incidence pyrhelimeter becomes pertinent [9, 10]. Further, in the presence of appreciable atmospheric pollution the flux density is likely to vary rapidly with time, in a random fashion; possible differences in time constants of the two instruments gives rise to additional uncertainty in the calibrations.

#### DEVELOPMENT OF NEW CALIBRATION PROCEDURE

It is apparent, then, that ambient temperature, angle of incidence, and degree of pollution all exert some effect on the calibration obtained for the standard Eppler, and that in general to every set of these three elements there corresponds a calibration constant. The magnitude of the effects of angle of incidence and temperature are shown in [8], but we have not measured the magnitude of the pollution effect. A new calibration procedure should take account of these elements in the calibration of the Eppler standard and in calibration of the pyrhelimeters used in the radiation network. The two phases of the process are treated here as separate problems.

##### THE PYRANOMETER AS A STANDARD

On May 3, 1952, the authors outlined the project to Mr. L. B. Aldrich and the late Mr. W. H. Hoover, of the Smithsonian Institution, and requested their advice on the problem of improving the calibration of the standard Eppler. Their reply stressed the adverse effects of the shade-rings. They suggested that a substantial im-

provement in precision of calibrating the standard Eppler could be expected through the use of the Smithsonian pyranometer [11, 12], and gave convincing arguments to that effect.

The pyranometer is a compensation-type pyrhelimeter which can be exposed to measure normal-incidence flux density when shielded from sky radiation by means of an apertured tube such as is used on the silver-disk and water-flow. The instrument can also be used to measure total solar and sky radiation on a horizontal surface by removing the tube. It is equipped with a precision-ground hemispherical quartz envelope of uniform thickness. The tube is constructed with the object that the angular area about the sun "seen" by the instrument when measuring only direct solar radiation should match as closely as possible that of the silver-disk against which it is calibrated.

An examination of the data on calibration of the pyranometer against the Smithsonian silver-disk at Mount Wilson at normal incidence, kindly supplied by Mr. Aldrich, showed a mean deviation from average calibration amounting to about 0.2 percent of the mean calibration. Table 6 contains calibration data for the pyranometer.

TABLE 6.—Calibrations of pyranometer no. 14 against silver-disk A. P. O. 8 bis. (Basic data source: Mr. Aldrich, Smithsonian Institution)

Date	Number of comparisons	Mean constant	Deviation from mean
May 7, 1952, a. m.	8	18.485	0.025
May 7, 1952, p. m.	8	18.468	.008
May 7, 1952, p. m.	6	18.465	.005
May 15, 1952, p. m.	4	18.462	.002
May 27, 1952, a. m.	8	18.451	.009
May 27, 1952, p. m.	8	18.505	.045
May 27, 1952, p. m.	8	18.506	.045
June 2, 1952, a. m.	8	18.491	.031
June 3, 1952, a. m.	8	18.451	.009
July 13, 1952, a. m.	10	18.403	.057
July 14, 1952, a. m.	9	18.492	.032
July 14, 1952, a. m.	10	18.335	.135
July 14, 1952, p. m.	6	18.478	.018
July 14, 1952, p. m.	10	18.452	.008
July 15, 1952, p. m.	10	18.431	.029
April 7, 1953, a. m.	6	18.493	.033
Mean		18.460	.030
			.030/18.460 equals about 2(10 <sup>-4</sup> )

It was decided then to accept the advice of Mr. Aldrich and Mr. Hoover, and to take advantage of their kind offer to cooperate in our program by furnishing and operating the pyranometer, and a procedure for calibration of a standard Eppler against the pyranometer was arranged.

##### CALIBRATION OF THE STANDARD EPPLER AGAINST THE PYRANOMETER

The requirements that the radiation field and ambient temperature be standardized and pollution effects suppressed in the calibration process suggest that laboratory processes are desirable. Early in the study of the problem, it appeared that the use of a radiation integrating sphere would provide a solution since the great precision in measurement of distances generally involved in optical-bench setups is not necessary in the integrating sphere. The uniform flux density constituting the radiation field in the sphere is desirable since possible directional effects

due to small irregularities in the glass envelope and detector sensitive surface are integrated. Ambient temperature varies over but a small range since the sphere is in a well-insulated building; and pollution effects are eliminated. The authors decided to carry out a program of calibration of a standard Eppley out-of-doors under clear-sky conditions on days of minimum pollution and to compare the results with calibrations of the same Eppley, against the pyranometer, in an integrating sphere. An excellent integrating sphere located at the National Bureau of Standards, Washington, D. C., was found to be available.

*Calibration with sun as source.*—Through the good offices of Dr. W. F. Shenton, head of the mathematics department of American University, Washington, D. C., permission for use of the attic and roof of Hurst Hall on the university campus was kindly granted by the president of the university, Dr. H. R. Anderson. The exposure there is one of the best available in the Washington area, being almost completely free from obstructions to the nearly flat horizon, and having relatively few important local sources of atmospheric pollution. Six Eppleys were installed on the roof and leads were run down a ventilating shaft to the attic in which the auxiliary measuring apparatus was installed. Mr. Aldrich and Mr. Hoover, who handled all details of the pyranometer work, installed the pyranometer within about 2 feet of the center of the cluster of pyrhemometers. Their auxiliary measuring equipment was also installed in the attic. Since one of the pyrhemometers exposed (No. 1973) previously had been subjected to numerous tests to determine its characteristics, it was chosen to be the standard. The others were exposed to provide a margin against damage to No. 1973.

Operation of the pyranometer requires that the detector unit be exposed to the sun for 20 seconds by the flipping open of a solenoid-operated lid and that the immediate deflection of a ballistic-type galvanometer be read. The lid is then closed and electric power is metered to a strip of the detector in quantity sufficient to produce a galvanometer deflection matching that observed when the unit was exposed to sun and sky. The observer then records the current, as read from a suitable meter. (Full details of the pyranometer are given in [11, 12].) To coincide with an observation made with the pyranometer, a reading of the pyrhemometer was made at the instant the lid to the pyranometer was flipped open. A system of buzzers made it possible to synchronize the observations of pyranometer and pyrhemometers satisfactorily. Buzzer and solenoid were controlled automatically by timing switches. Two observers operated thermocouple switches to connect the pyrhemometers to portable potentiometers. Each observer began a series of readings on the three pyrhemometers assigned to him when the buzzer signaled that the pyranometer lid had opened. The sequence of reading of the pyrhemometer voltages was reversed by each observer on each successive calibration to avoid hav-

ing a systematic time displacement between any of the pyrhemometer readings and those of the pyranometer. A series of readings was taken every  $2\frac{1}{2}$  minutes. It took an observer about 40 seconds to read the 3 pyrhemometers. Readings were taken both in the forenoon and afternoon.

Readings of ambient temperature were obtained by means of a resistance thermometer, the sensing element of which was shielded from the sun and mounted among the pyrhemometers. A wheatstone bridge unit, connected to the thermometer element, was mounted near one of the portable potentiometers in the attic.

When these arrangements had been completed, a day of clear weather, with a level of atmospheric pollution as low as might be expected in any reasonable length of time, was awaited. Such a day occurred on August 25, 1952, and the first measurements were made then. On that date 97 calibration sequences were taken, spanning a range of solar elevations from  $62^\circ$  to  $24^\circ$ . The following day was also suitable and 106 sequences were taken spanning solar elevations from  $61^\circ$  to  $24^\circ$ . Other observations were obtained on January 26 and February 9, 1953, but the elevation angles were so small that the data were of only secondary importance; e. g., testing temperature effects. Processing of data consisted of the following steps for each sequence:

1. Tabulation of Eastern Standard Time of the beginning of the sequence.
2. Computation and tabulation of the corresponding apparent solar time.
3. Computation and tabulation of solar altitude.
4. Tabulation of the voltage output for each of the pyrhemometers.
5. Tabulation of the corresponding flux density measured by the pyranometer.
6. Determination of the calibration constants by dividing millivolts output by flux density to obtain millivolts/langleys per minute.
7. Tabulation of ambient temperature.

The above provided the desired fundamental data. Various studies were made attempting to reconcile laboratory data on cosine response and ambient temperature with similar data obtained in the calibrations at American University—"sun calibrations". These were not entirely successful, and indicated the possibility of a cosine-response effect in the pyranometer and suggested the form and amount. Subsequent tests on the pyranometer at the Smithsonian Institution did not bear out the details of the suggested cosine curve, but did indicate that there was a small cosine effect in the pyranometer and that the best results in calibrating the Eppley against the pyranometer using the sun as source could be expected at low values of angle of incidence, corresponding to those at which the pyranometer had been calibrated against the silver-disk. Accordingly, to represent the sun calibration of Eppley standard No. 1973, an average calibration over the angle-of-incidence interval  $28^\circ$  to  $60^\circ$  ( $28^\circ$  being the smallest angle of incidence at which data were ob-

tained, and the span  $28^{\circ}$  to  $60^{\circ}$  being an interval of nearly constant small slope in the cosine curve) was computed as representative of the constant for the midpoint of that interval—i. e., angle of incidence  $44^{\circ}$ . As mentioned, these data were obtained on August 25 and 26, 1952. Temperature conditions during the two days were quite similar. Average ambient temperature was about  $75^{\circ}$  F. (While [8] shows that the temperature effect is not quite linear, departure from linearity introduces no more than a trivial difference from the mean temperature obtained by an arithmetic averaging.) The calibration figure obtained is:

Pyrheliometer No. ....	1973.
Calibration Constant (millivolts/langleys per minute) .....	2.40.
Angle of incidence .....	$44^{\circ}$ .
Ambient temperature .....	$75^{\circ}$ F.

*Calibration in the integrating sphere.*—While the calibrations were being carried out at American University, arrangements were made for carrying out calibration work at the National Bureau of Standards integrating sphere, through the generous cooperation of Mr. Ray Teele, of the Radiometry Section of the Division of Optics, in the Materials Testing Building of the National Bureau of Standards in Washington, D. C.

The integrating sphere (see [13] for theory) is about 15 feet in diameter. It is arranged with hinges and casters to open along a vertical diametrical plane, giving ready access to the interior. The walls of the interior are painted with a special highly reflective magnesium oxide paint. The radiation source is a tungsten-in-glass lamp of 2,500 watts, the voltage to which was controlled during our operations by means of a variable transformer, spanned by an accurate a. c. voltmeter. Temperature of the filament was estimated by Mr. Teele as about  $2,800^{\circ}$  K.

On two separate occasions (March 23, 1953, and April 1, 1953) the pyranometer and pyrheliometer No. 1973 were set up in the integrating sphere. Calibrations obtained were 2.343 and 2.334, respectively, at ambient temperatures  $85^{\circ}$ – $90^{\circ}$  F. The mean of these calibrations is 2.34 to the nearest hundredth. This figure can be corrected to ambient temperature  $75^{\circ}$  F. by reference to data in [8]; the resulting constant is 2.36. Summarizing,

Out of doors at American University, calibration	millivolts/langleys
at ambient temperature $75^{\circ}$ F. ....	per minute
Integrating sphere: calibration, reduced to $75^{\circ}$ F. ..	2.40
	2.36

These values disagree by about 1.7 percent.

#### DISCUSSION OF RESULTS

The difference of 1.7 percent in the calibrations obtained in the integrating sphere and out of doors requires comment. Conditions in the integrating sphere differ in two essential respects from those existing at American University during the work there. They are (1) the spectral distribution of radiation from the radiation source (sun and sky at American University vs. the  $2,800^{\circ}$  K. incandescent tungsten-in-glass lamp in the integrating sphere),

and (2) radiation "field" (uniform diffuse flux density in the sphere vs. largely unidirectional radiation from an angle of incidence varying from  $22^{\circ}$  to  $65^{\circ}$  at American University).

If the pyrheliometer and pyranometer differ with respect to spectral response over the intervals of the spectrum involved in the two tests, the results might be reflected in a discrepancy between the calibrations of the pyrheliometer obtained in those tests. An experiment performed in the laboratory (described in the appendix) indicated that such an effect would influence the calibration by not more than about one-tenth of one percent. Evidently the observed discrepancy of 1.7 percent cannot be ascribed to spectral considerations.

Differences in the radiation field can influence the calibration of the pyrheliometer due to the differing cosine response characteristics of the two instruments. If sufficiently comprehensive data were available for both instruments, it would be possible to compute the magnitude of the effect and so verify the hypothesis that the discrepancy arises from cosine characteristics. This would require data for angles of incidence and azimuth corresponding to the solar paths "seen" by each instrument during the tests since, especially in the pyrheliometer, there is a small random variation in calibration with azimuth as well as angle of incidence. It hardly seems feasible to do this at present. The cosine response data available for the pyrheliometer suggest that the integrator calibration should be slightly lower than the out-of-doors calibration and it is believed likely that a large part of the 1.7-percent discrepancy arises from the pyrheliometer cosine characteristic and cannot be suppressed without substantial (and probably expensive) improvements in the pyrheliometer.

The question now arises as to which calibration to assign the instrument. In the aggregate, it seems likely that more record will be taken with the sun obscured by clouds than with the sky clear and the sun near  $45^{\circ}$  (or any other specified) angle of incidence. The former condition corresponds very roughly to the sphere calibration conditions, the latter to the American University calibrations. On this basis, calibration under the diffuse radiation of the integrating sphere calibration seems preferable and is taken as definitive. An analysis of the cosine response of pyrheliometer No. 1973 together with the Moon-Spencer [14] cloudy-sky radiation distribution also indicates the sphere calibration is preferable for cloudy-sky conditions.

#### CALIBRATION OF FIELD PYRHELIOMETERS AGAINST THE STANDARD EPPLEY

Use of the integrating sphere makes it possible for two men to easily calibrate a dozen pyrheliometers in a day against the standard Eppley. Experience to date on about 50 pyrheliometers has shown that without exception the calibration is reproducible to better than one percent accuracy.

## THE QUESTION OF PYRHELIOMETRIC SCALE

The concept of "pyrliometric scale" arises in the following way. The water-flow pyrliometer [2] was established in the period 1910 to 1913 as the standard pyrliometer by the Smithsonian Institution. From time to time since then, improvements have been made in the water-flow pyrliometer, each of which led to an estimation of the systematic error involved in previous measurements with the water-flow and hence of instruments calibrated against it, directly or indirectly. However, in order that measurements with field instruments should be kept comparable over the years, in general, this systematic error, while recognized, was not corrected for in the field measurements. This has proved to be a sound policy, in view of the several changes in "scale" which would otherwise have greatly complicated comparisons of observations over a period of years.

The Weather Bureau has observed such a policy in its field measurements [6, p. 418], and while there are several arguments pro and con on the problem of changing to a basis eliminating all known systematic error insofar as possible, the policy of the Weather Bureau has not been changed and for the time being at least the basis of calibration remains the "Smithsonian scale of 1913." Present opinion [5, p. 7] is that the 1913 scale is 2.5 percent too high. This indicates that field measurements calibrated to the 1913 scale give data systematically 2.5 percent too high.

## SUMMARY

A system for calibrating the standard Eppley against the pyranometer has been devised and placed in effect. A new system for calibration of the pyrliometers used in the network has also been devised and placed in effect. The latter system, which involves comparison calibrations against a standard Eppley in an integrating sphere, makes it possible for two men to calibrate a dozen pyrliometers a day with reproducibility accurate to better than one percent. Previously, two men could calibrate only about 3 pyrliometers a day, and then only during the rare occasions when skies were clear and atmospheric pollution at a minimum, and with repeatability of about 3 percent.

The new calibration linkage from water-flow normal-incidence pyrliometer to field pyrliometer is now the following:

1. By the Smithsonian Institution: (a) Absolute calibration of the water-flow normal-incidence pyrliometer. (b) Calibration of the Smithsonian Institution silver-disk pyrliometer by direct comparison with the water-flow pyrliometer. (c) Calibration of the pyranometer by direct comparison with the Smithsonian silver-disk pyrliometer.
2. By the Smithsonian Institution and Weather Bureau jointly: Calibration of the standard Eppley against the pyranometer.

3. By the Weather Bureau: Calibration of pyrliometers used in the radiation network in the integrating sphere against the standard Eppley.

The calibrations are based on the 1913 scale, as heretofore.

## APPENDIX

In the case of the calibration of the Eppley standard against the pyranometer, the method consists essentially of a determination of the flux density  $Q$  by means of the pyranometer and the millivolts  $e_e$  simultaneously generated by the Eppley, both instruments being exposed to the sun and sky. The calibration constant  $C$  is then

$$C = e_e / Q$$

A sufficient condition that a calibration under a radiation source other than sun and sky be accurate when measuring sun-and-sky radiation is that  $e_e/Q$  as determined under the calibration source should be the same as  $e_e/Q$  measured under sun-and-sky radiation source. It is desired then to determine whether  $e_e/Q$  given with the tungsten lamp as a radiation source is the same as  $e_e/Q$  with the sun as the source.

It is difficult to make a direct comparison, by attempting to obtain a calibration from the two sources at identical angles of incidence. It is very much simpler to obtain ratios by using the unfiltered tungsten lamp as a source first, and then by using the same source with a water filter, as is described in the following experiment:

The pyranometer and pyrliometer were mounted on opposite sides of a precision turntable, above which was mounted a tungsten lamp similar to the one used in the integrating sphere and with the same voltage across its terminals. The turntable was equipped with a vernier for precisely positioning the detectors.

With the lamp turned on (power was fed through a voltage stabilizer and regulator), the pyranometer and pyrliometer were successively placed beneath the lamp and readings taken. A water-cell filter, consisting of about one-eighth inch of glass and 4 cm. of water, was introduced into the radiation beam and readings were repeated. The calibration constants computed under the two radiation fields agreed within one-tenth of 1 percent. This indicates that the relatively large amount of radiation coming in at wavelengths greater than 1 micron from the unfiltered tungsten lamp introduces no error greater than 0.1 percent into the calibration of the pyrliometer.

Figure 2 shows spectral distribution of radiation from the tungsten lamp, with and without the water filter, together with solar radiation spectral distribution [15]. The first two were computed from spectral distribution of radiation data for tungsten at 2,800° K. (estimated by Ray Teele as being the temperature of the tungsten lamps used during the calibration in the integrating sphere) together with liquid water transmission data [16] and trans-

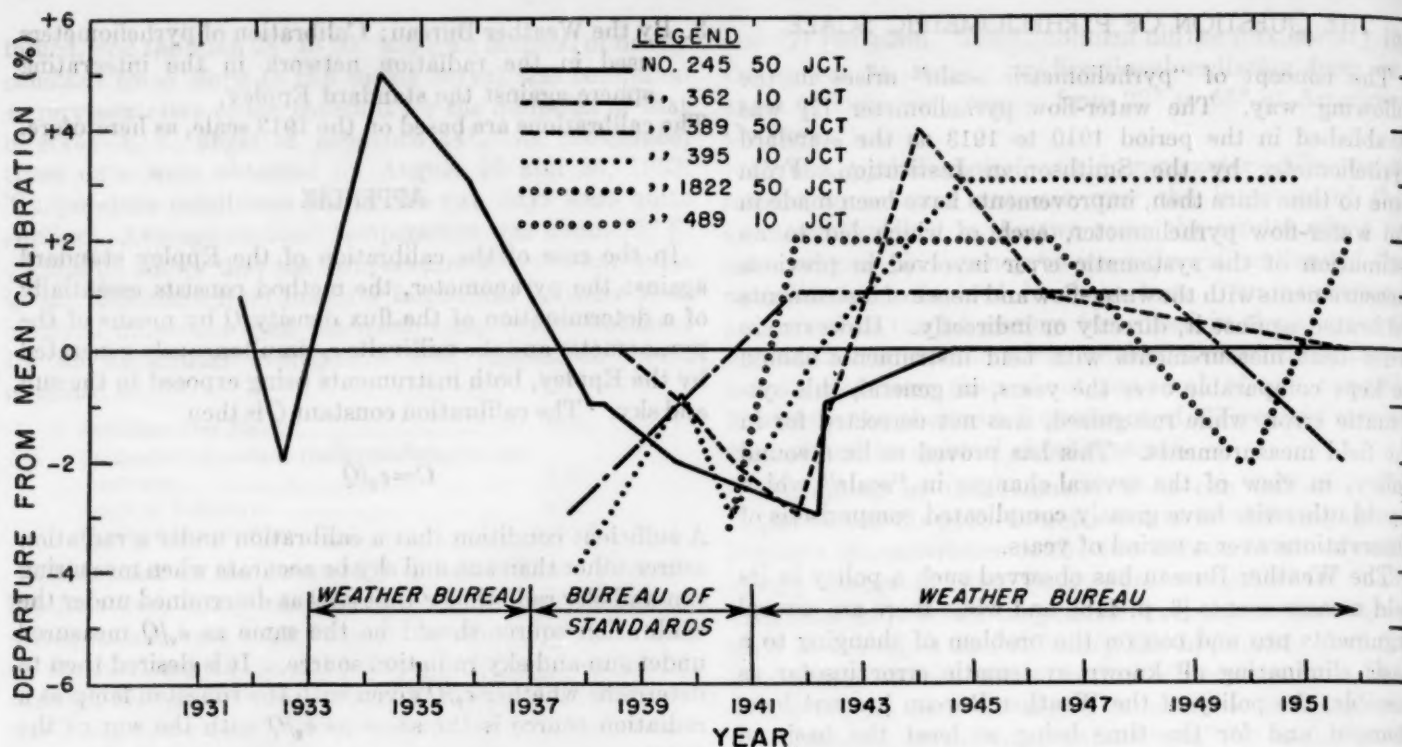


FIGURE 2.—Normalized transmission curves of solar radiation and tungsten-lamp radiation with and without the water filter.

mission data for glass.\* The water cell reduces the proportion of radiation from wavelengths greater than 1 micron from 87 percent to 33 percent—i. e., from more than solar radiation amount to less than that for solar radiation.

Further examination of figure 2 shows that the introduction of the water-glass filter into the radiation beam from the tungsten filament lamp does not produce radiation matching the solar radiation, but that the tungsten is displaced somewhat to the long-wave side of the solar distribution curve. The question arises as to the possible differences in ratio of response of the pyranometer and pyrliometer under these two slightly different spectral distributions.

The coverings of the two instruments are different. The pyranometer is covered with a quartz envelope, whereas the Eppler cover is glass. The receiving surface of the pyranometer is finely divided carbon as is the black receiving element in the Eppler. There is no surface in the pyranometer corresponding to the white receiving annular ring of the Eppler, under which the cold junctions of the thermopile are located. It appears from this that if there are differences in relative response of the pyranometer and pyrliometer with the change in spectral distribution in question, they must arise from differences in

relative transmission of the two covers, or from variations in the spectral reflectance of the white element in the Eppler, or from both.

An examination of the data indicates no measurable change in the relative transmissions of glass and quartz from 0.4 to 1 micron. Data for spectral reflection of MgO by Middleton [17] show no considerable change in spectral reflectivity of MgO in the region. It appears that the spectral effects on the calibration do not exceed about 0.1 percent.

#### ACKNOWLEDGMENTS

We wish to thank Mr. Ray Teele, of the National Bureau of Standards, for making available for our work the integrating sphere and auxiliary equipment; and Dr. W. F. Shenton and Dr. H. R. Anderson for providing facilities at American University. We extend thanks also to Eppler Laboratories and particularly Mr. Hedley Greer for providing needed data; to Dr. Sigmund Fritz for reading the manuscript and suggesting the inclusion of a paragraph on the scale of pyrliometry; Mr. C. L. Mateer, of the Canadian Meteorological Service, for contributing to the editing; and Mr. Benjamin LeBlanc for extensive computational work. The project would have been impossible without the participation of Mr. Lyle B. Aldrich and the late Mr. W. H. Hoover of the Smithsonian Institution.

\*Glass transmission data by Corning Glass Works, National Bureau of Standards, and General Electric Co.

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# THE WEATHER AND CIRCULATION OF AUGUST 1954<sup>1</sup>

## Including a Discussion of Hurricane Carol in Relation to the Planetary Wave Pattern

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### PERSISTENCE OF THE WEATHER REGIME

The weather experienced over much of the United States in August 1954 was basically similar to the prevailing weather regime of the two preceding summer months [1,2.] August temperatures were greater than normal over a large section of the country extending from the Rockies to the Atlantic coast, while cooler-than-normal weather prevailed along the northern tier of States and in the Far West (Chart I-B). Precipitation east of the Rockies was mostly subnormal where warm weather prevailed, but was in excess of normal near the boundary zone between above and below normal temperatures (Chart III). These weather patterns were essentially characteristic of the entire summer of 1954, as is clearly demonstrated by the close similarity of Charts I-B and III-B to the seasonal temperature and precipitation anomalies portrayed in figure 1. For about three-quarters of the Nation the summer of 1954 was mainly hot and dry. In sharp contrast the west coast, the Northwest, and the Northeast experienced a summer which was predominantly cool and wet.

Going somewhat farther afield, Great Britain and adjacent portions of northwestern Europe suffered through a summer that was cold, cloudy, and wet—a spell of bad weather which had set in as early as May. Long spells of

weather, especially in the summer season, are not uncommon in Great Britain according to a recent study by Lamb [3]. For the United States, Namias [4] has demonstrated that the maximum monthly persistence of temperature occurs between July and August with relatively high persistence also apparent between June and July. Precipitation and the circulation pattern also persist in summer, but to a lesser extent than temperature. The remarkable fact about this summer was that persistence of temperature, precipitation, and circulation was much more pronounced than usual.

### THE CIRCULATION PATTERN OF AUGUST 1954

Over the United States the mean circulation pattern at 700 mb. during August 1954 (fig. 2) again consisted of deeper-than-normal troughs near each coast and a stronger-than-normal continental anticyclone dominating the southern half of the country. This continental anticyclone, with center over Alabama in August, first developed in June [1], persisted through July [2], and even by the end of August still prevailed over the central United States. The central anomaly of this anticyclone (+110 feet) was slightly greater this month than it was in the two preceding months. The association of such a stronger-than-normal upper level anticyclone with summertime

<sup>1</sup> See Charts I-XV following p. 247 for analyzed climatological data for the month.

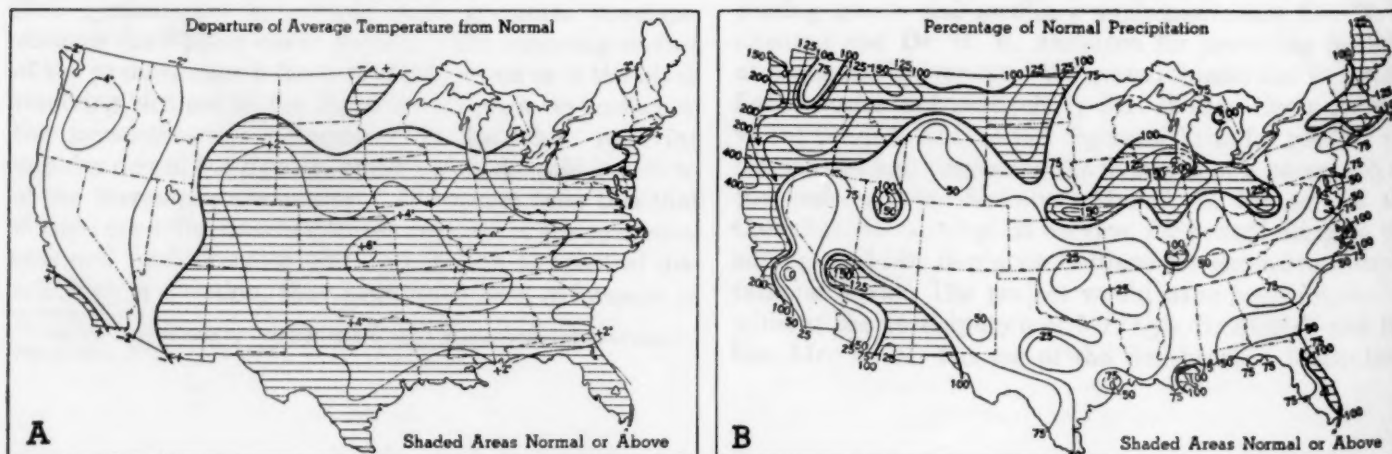


FIGURE 1.—(A) Departure of average temperature from normal, and (B) percentage of normal precipitation, both for the summer (June-August) of 1954. Most outstanding was vast area of country with hot, dry weather.

heat and drought over the United States has been pointed out many times since the early findings of Reed [5]. This relationship was again discussed in connection with the heat and drought of the preceding two months of this summer by Holland [1] and Hawkins [2].

Associated with this persistence of the circulation pattern over the United States was a general persistence in location and intensity of the five planetary troughs in the circulation of the Northern Hemisphere at middle latitudes. (Compare fig. 2 with fig. 1 of [2].) In each of these troughs heights were below normal this month, but in only two of the ridges in this wave train, those over Siberia and the eastern Pacific, were heights consistently

above normal at middle latitudes. Over the region from the trough along the west coast of the United States eastward to the trough along the 70° E. meridian, channels of negative height anomaly extended zonally through the ridges and connected the negative height anomaly centers located in the troughs. The channel across the northern United States was weakest since the continental ridge was still above normal as far north as the southern end of the Great Lakes, but this represented a considerable drop in anomaly in this region from the predominantly positive anomalies of July. From these considerations then the wave pattern during August could be characterized as one of large amplitude over Siberia and the Pacific

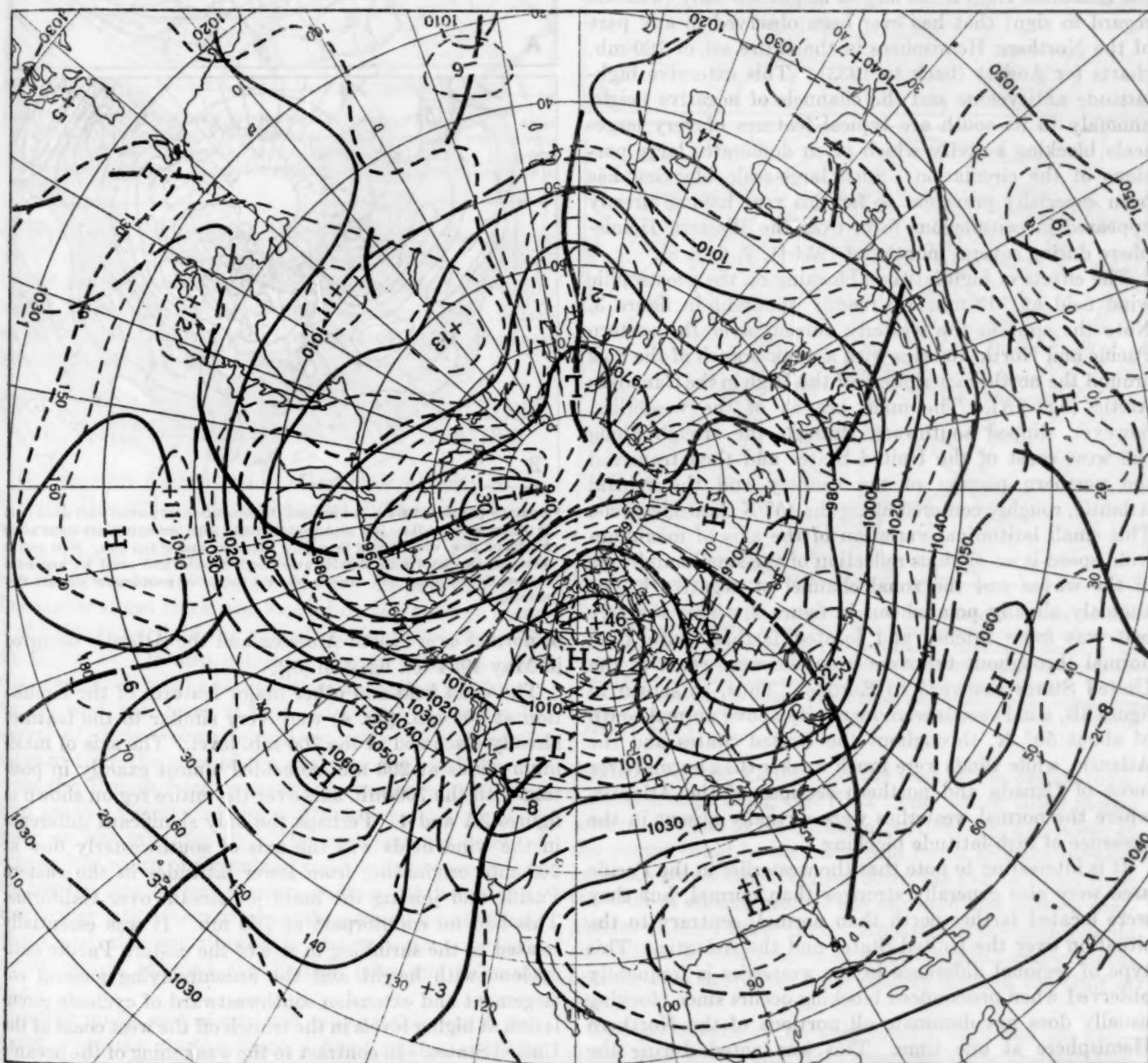


FIGURE 2.—Mean 700-mb. contours and height departures from normal (both in tens of feet) for July 31-August 29, 1954. Over North American area major circulation features were deeper-than-normal troughs along each coast with stronger-than-normal continental anticyclones over northern Canada and southern United States. Height anomaly of +460 feet over Canada is largest ever observed in August.

while relatively small amplitude waves covered the United States, the Atlantic, and Europe even though the troughs were deep.

Closely associated with these small amplitudes engendered by weak subtropical ridges at middle latitudes was an extensive anticyclonic circulation which covered most of the higher latitude sections (north of  $55^{\circ}$ – $60^{\circ}$  N.) of the Western Hemisphere. The major center of this anticyclone was located over northwestern Canada while a minor High cell was located over Greenland. Heights were considerably above normal throughout all of northern Canada, Greenland, and eastern Alaska. The maximum anomaly center of +460 feet located to the northeast of the Canadian High is the largest height anomaly (without regard to sign) that has ever been observed in any part of the Northern Hemisphere in the entire set of 700-mb. charts for August (back to 1933). This extensive high-latitude anticyclone and the channels of negative height anomaly to its south are typical features of very large-scale blocking activity which often dominates large portions of the circulation. Such large-scale blocking has been especially prevalent so far this year having already appeared in conspicuous form over the Western Hemisphere during several months of 1954 [1, 2, 6, 7, 8].

The effects of high-latitude blocking on the geostrophic wind field at 700 mb. are readily apparent in figure 3. Note the split in the westerly current over the eastern Pacific and North America with a weak branch of the flow around the northern periphery of the High in the Canadian Arctic (fig. 3A). The main branch of the westerlies, however, dipped southward through the trough along the west coast of the United States and then traversed the northern portion of the country and the central Atlantic, roughly centered along the  $45^{\circ}$  N. latitude circle. This small latitudinal variation of the axis of maximum wind speed is an obvious reflection of the small amplitude of the waves and the zonal channel of negative height anomaly already pointed out in figure 2. This westerly belt was more intense and located farther south than normal throughout the zone from the west coast of the United States eastward to Europe. Thus, as shown in figure 3B, wind speeds were markedly above normal south of about  $50^{\circ}$  N. throughout the United States and the Atlantic, while winds were much weaker than normal over most of Canada and northern sections of the Atlantic, where the normal westerlies were virtually absent in the presence of high-latitude blocking.

It is interesting to note that the westerlies in the Pacific area were also generally stronger than normal, but they were located farther north than normal, contrary to the situation over the United States and the Atlantic. This type of regional difference in the westerlies is frequently observed when pronounced blocking occurs since blocking usually does not dominate all portions of the Northern Hemisphere at one time. This was noted during the intense index cycle of February 1952 [9]. A recent case of westerlies north of normal over the Pacific and south

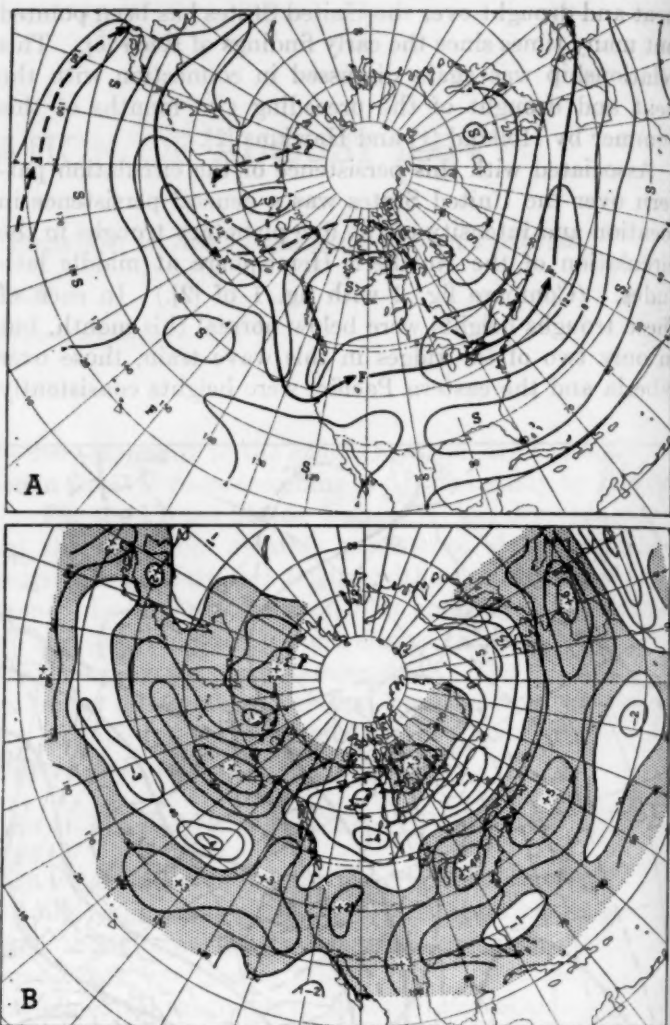


FIGURE 3.—(A) Mean 700-mb. isotachs and (B) departure from normal wind speed (both in meters per second) for July 31–August 29, 1954. Solid arrows indicate major axis of maximum flow, while dashed lines show secondary axes of fast flow. Note split in westerlies associated with blocking over North America and zonal jet axis across eastern United States and Atlantic where winds were considerably stronger than normal.

of normal over North America and the Atlantic occurred in May 1954 (cf. fig. 4 of [8]).

The wind field and other major features of the circulation at 200 mb. (fig. 4) were very similar to the features already discussed at the 700-mb. level. The axis of maximum winds at 200 mb. coincided almost exactly in position with the 700-mb. axis over the entire region shown in figures 3A and 4. Perhaps the only significant difference in the wind fields was the axis of southwesterly flow at 200 mb. originating from lower latitudes in the eastern Pacific and joining the main jet stream over California. This had no counterpart at 700 mb. It was essentially related to the shrinking in size of the eastern Pacific anticyclone with height and the accompanying general enlargement and extension southwestward of cyclonic circulation at higher levels in the trough off the west coast of the United States. In contrast to the weakening of the oceanic anticyclonic circulations with height (note the disappearance of the Atlantic High center altogether) both anti-

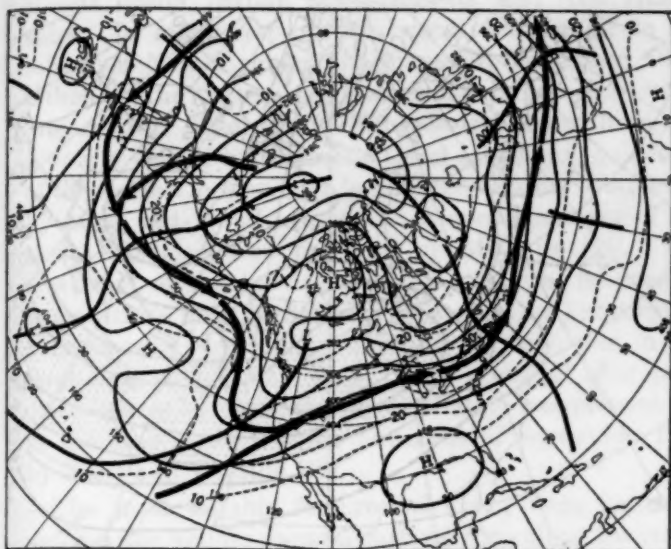


FIGURE 4.—Mean 200-mb. contours (in hundreds of feet) and isotachs (dashed, in meters per second) for July 31–August 29, 1954. Solid arrows indicate the axes of monthly mean jet stream. Circulation pattern and jet axis are very similar to 700-mb. features of figures 2 and 3A except for increased cyclonic circulation and southwestward tilt of west coast trough.

cyclones over continental North America, the one in northwestern Canada and the other over the southern United States, maintained their strength at the 200-mb. level. These are most likely manifestations of the differences in the tropospheric temperature fields between continents and oceans in summer.

#### CIRCULATION RELATED TO TRACKS OF CYCLONES AND ANTICYCLONES, FRONTS, AND WEATHER

The greatest concentration of cyclonic activity in the Western Hemisphere during August 1954 occurred in a relatively narrow zone extending from the northeast coast of the United States out into the east-central Atlantic between latitudes  $45^{\circ}$  and  $50^{\circ}$  N. (fig. 5A and Chart X). This major storm track was located on the average about  $3^{\circ}$  of latitude north of the axis of maximum winds at 700 mb. (fig. 3A). It also coincided closely with the zonal axes of negative height and pressure anomalies at 700 mb. (fig. 2) and sea level (Chart XI inset), respectively. Several of these storms moved on eastward and northeastward from the edge of the analyzed data in figure 5A across the British Isles, generally deepening and slowing down in the vicinity of the  $-270$ -foot height anomaly center at 700 mb. (fig. 2). The more normal track of cyclones just south of Greenland was somewhat secondary this month, but several storms crossing the Atlantic at these higher latitudes moved southeastward across Great Britain and also contributed to the persistent cyclonic activity which afflicted the British Isles and adjacent areas.

Another major seat of cyclonic activity this month was located over the northwestern United States and the eastern slopes of the Continental Divide as far south as the Oklahoma Panhandle (fig. 5A). Most of these cyclones

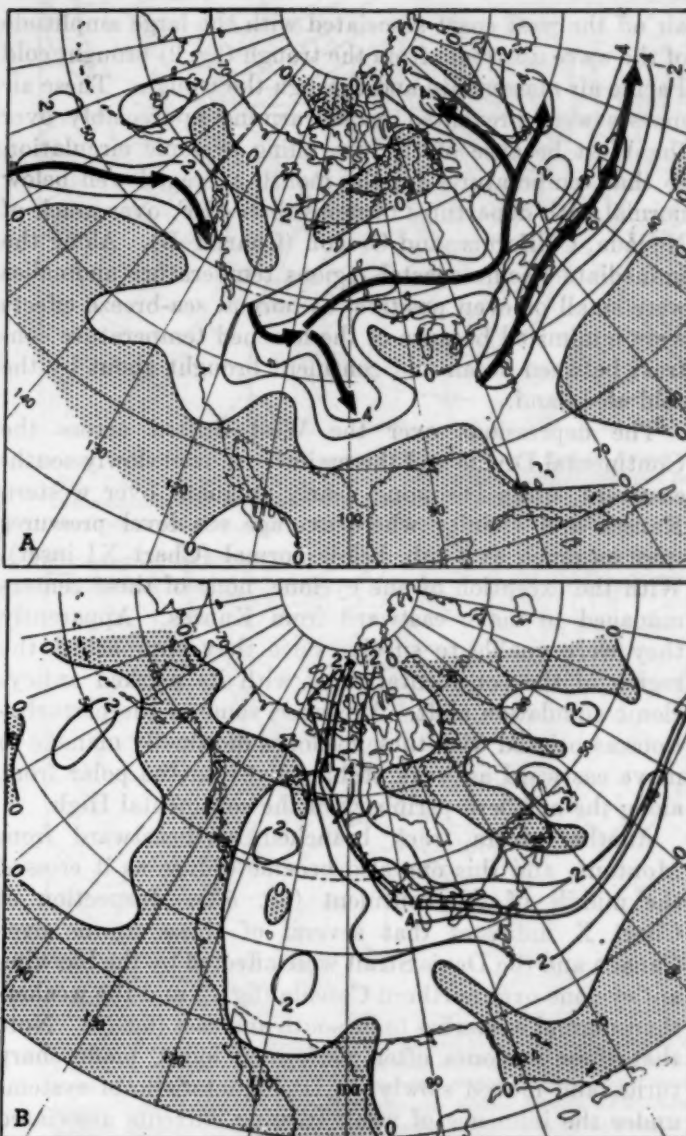


FIGURE 5.—Frequency of (A) cyclone passages and (B) anticyclone passages (within  $5^{\circ}$  squares at  $45^{\circ}$  N.) during August 1954. Well-defined cyclone tracks are indicated by solid arrows and anticyclone tracks by open arrows. Outstanding feature of anticyclones was well-established principal track of polar Highs originating over Canada and passing over Great Lakes and Middle Atlantic States into the Atlantic. Cyclonic activity was frequent in western United States, but few major storms moved across central and eastern North America due to the strength of continental anticyclones shown in figure 2.

formed over the Plateau, to the east of the deeper-than-normal trough along the West Coast which tilted inland toward Alberta in its northern portion (fig. 2). Most of the storms could be traced to cold fronts and accompanying weak waves which drifted down the Pacific Coast from the Gulf of Alaska around the northern and eastern peripheries of the Pacific High. Apparently the anticyclonic circulation in this ridge was so strong that major storm centers were prevented from passing through the Gulf of Alaska.

The prevalence of the west coast trough and the associated cyclones in the West produced more precipitation than normal along the Pacific coast and in the Northwest (Chart III). Meanwhile the strong northerly fetch of

air off the west coast associated with the large amplitude of the wave upstream from the trough (fig. 2) brought cold Pacific air masses into and through the trough. These air masses were prevented from warming appreciably over the West because of the prevailing cyclonic circulation so that temperatures for the month averaged well below normal with departures of more than  $4^{\circ}\text{F.}$  over much of Nevada, California, and Oregon (Chart I-B). Along the immediate Pacific coastal regions temperature anomalies were small or even positive, as normal sea-breeze effects were minimized because of the lessened temperature contrast between ocean and continent brought about by the cold air inland.

The depressions over the West drifted across the Continental Divide and the majority moved slowly south-eastward, often becoming nearly stagnant over western Kansas and vicinity where average sea level pressures were as much as 4 mb. below normal (Chart XI inset). With the exception of one cyclone, none of these centers managed to move eastward from Kansas. Apparently they were unable to survive once they approached the region of the continental ridge with its marked anticyclonic circulation aloft. However, some of the perturbations associated with these cyclones did finally manage to move eastward as weak stable waves on the polar front along the northern periphery of the continental High.

Another storm track branched northeastward from Montana, and this one also became diffuse as it crossed the middle of the continent (fig. 5A). Inspection of Chart X indicates that several of these storms over Canada and the Davis Strait were affected by the blocking anticyclone over northern Canada (fig. 2) and the weaker-than-normal westerlies to its south and east (fig. 3). Note that these cyclones often performed loops, made sharp turns, and moved slowly, as is characteristic of systems under the influence of weak steering currents associated with blocking Highs.

The huge mean anticyclone over northern Canada which had a closed center at sea level (Chart XI), 700 mb. (fig. 2), and 200 mb. (fig. 4) was quite naturally the seat of pronounced anticyclogenesis during August. Several of these developing Highs moved slowly or stagnated over northern and central Canada (Chart IX). From this region strong polar Highs followed a well-defined track south-southeastward to the Great Lakes and thence southeastward across the Middle Atlantic States into the Atlantic (fig. 5B), closely paralleling the mean 700-mb. flow (fig. 2). These anticyclones brought frequent outbreaks of cool continental polar air into the entire northern portion of the country eastward from the Dakotas so that temperatures averaged below normal (Chart I-B). In the first half of the month, blocking action was so pronounced over North America that rather deep penetrations of cold air into the southern United States occurred. These occasional major influxes of cold air were responsible for amelioration of the extreme heat over the South Central States in August as compared with July.

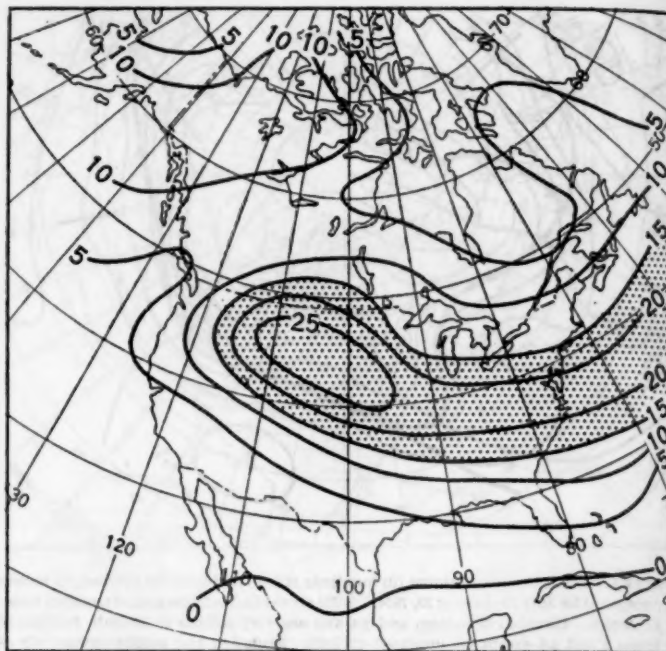


FIGURE 6.—Number of days in August 1954 with surface fronts of any type (within squares with sides approximately 500 miles). Frontal positions taken from *Daily Weather Map*, 1:30 p. m. EST. Note pronounced belt of frequent occurrence of fronts extending from middle Atlantic coast west-northwestward to Montana and Idaho. Heavier-than-normal precipitation occurred on northern side of this zone while markedly subnormal amounts occurred to the south (see Chart III).

For the most part, however, the southward drive of cold air masses was generally stopped about halfway down through the United States east of the Plains, because of the prevailing subtropical continental anticyclone aloft over the South. The boundary zone between the polar air and the tropical air was generally very well marked and tended to persist in much the same region throughout the month. This is clearly indicated in figure 6 which shows a pronounced concentration of fronts in a nearly zonal belt across the country from the middle Atlantic coast through the Ohio Valley and the Central Plains to the northern Rockies. This strong concentration of fronts provides a clear explanation for the general appearance of the monthly precipitation anomalies shown in Chart III. Since the fronts were largely aligned east-west, paralleling the axis of maximum frontal frequency, it is not at all surprising that rainfall amounts in excess of normal were located on the north side of this frontal concentration where overrunning took place, while amounts far below normal generally prevailed south of the frontal zone and throughout most of the area of the South dominated by the aforementioned continental anticyclone.

#### HURRICANE CAROL IN RELATION TO THE PLANETARY WAVE PATTERN

On the last day of August 1954 a devastating hurricane, designated as "Carol," moved rapidly up the Atlantic Coast and went inland over New England through

Rhode Island, eastern Massachusetts, and New Hampshire. In many respects this storm was similar to the infamous New England hurricane of September 1938, although the latter was somewhat larger and more intense [10]. The details of the destruction in lives and property caused by hurricane Carol as well as the details of the storm's motion have been covered rather completely by press, radio, and television. A good summary of the storm has also been prepared by McGuire [11]. The treatment of this hurricane in this article is designed to demonstrate how its behavior was governed, at least in a gross sense, by some interesting developments in the large-scale circulation. This type of "control" of tropical disturbances by the planetary circulation was pointed out in the case of the Florida hurricane of September 1947 by Klein and Winston [12].

The most notable features of Carol were its rapid acceleration and its unusual path right up along the coast, over the eastern tip of Long Island, and inland over New England instead of turning northeastward into the Atlantic. This acceleration and more northerly course of the storm were related to the development and intensification of a long-wave trough of large amplitude farther west over the eastern United States than it had been in the preceding few weeks. These large-scale circulation changes are illustrated by a series of three 5-day mean 700-mb. charts at half-week intervals in figures 7 to 9.

During the period August 21-25, 1954 (fig. 7), a large subtropical anticyclone (slightly east of the monthly mean position) dominated the circulation over the eastern two-thirds of the United States while a deep trough occupied the Far West. However, the wave amplitude in the Pacific had just increased and the deep trough in the central Pacific and the very strong ridge in the eastern Pacific were both retrograding at this time. A constant absolute vorticity trajectory computed in the mean northwesterly flow east of this ridge off the west coast indicated some retrogression and/or development for the west coast trough, the United States ridge, and the trough near the east coast.

By the next period, August 25-29, 1954 (fig. 8), the trough in the West had retrograded off the coast and the ridge over the United States had also moved westward some 10° of longitude. Note how heights began to fall over the eastern United States in response to the increase in cyclonic vorticity indicated by the vorticity trajectory from upstream in figure 7. By this time the hurricane had formed near the Bahamas and was moving very slowly northwestward (see path in fig. 9) in a region south of the main westerlies and north of the subtropical easterlies. This slow-moving tropical cyclone was reflected in the closed Low and mean trough in that area (fig. 8). A vorticity trajectory calculated in the southwesterly flow ahead of the west coast trough indicated slightly more retrogression for the ridge over the central United States, an intensifying trough along the east coast, and the buildup of a ridge in the western Atlantic. If these trends were

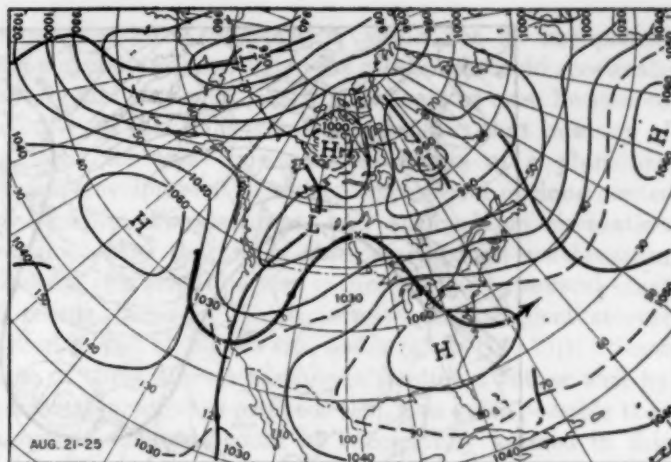


FIGURE 7.—Five-day mean 700-mb. contours (labeled in tens of feet) for August 21-25, 1954. Constant absolute vorticity trajectory originating in northwesterly flow east of large-amplitude ridge in eastern Pacific indicates retrogression and/or development of trough along west coast, ridge over eastern United States, and trough near east coast.

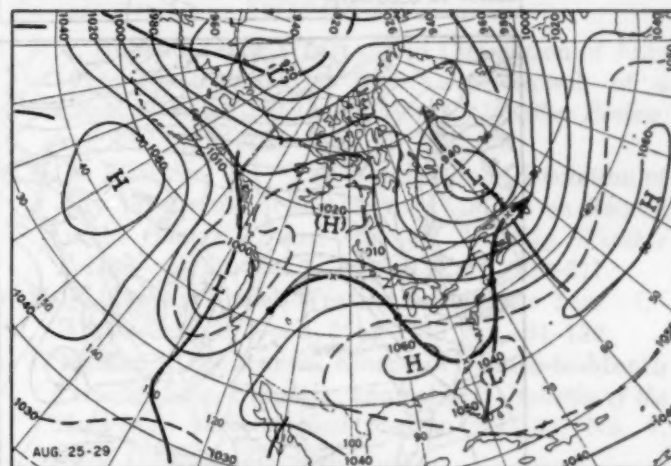


FIGURE 8.—Five-day mean 700-mb. contours (labeled in tens of feet) for August 25-29, 1954. Note retrogression of trough off west coast and ridge over United States as compared with previous map. Further retrogression of ridge, development of trough in eastern United States, and buildup of ridge over western Atlantic are indicated by constant absolute vorticity trajectory originating in southwesterly flow east of deep west coast trough. Note closed Low and trough off southeast coast associated with hurricane Carol.

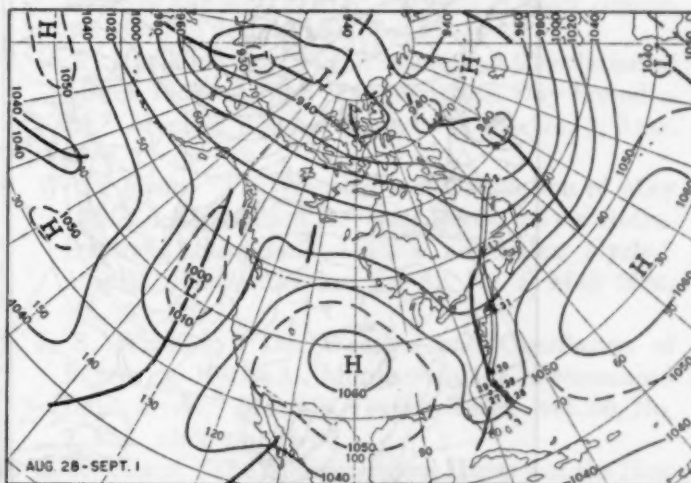


FIGURE 9.—Five-day mean 700-mb. contours (labeled in tens of feet) for August 29-September 1, 1954. Note path of hurricane Carol in relation to newly established trough along east coast. Further retrogression of west coast trough and United States ridge has occurred and ridge has built up over western Atlantic.

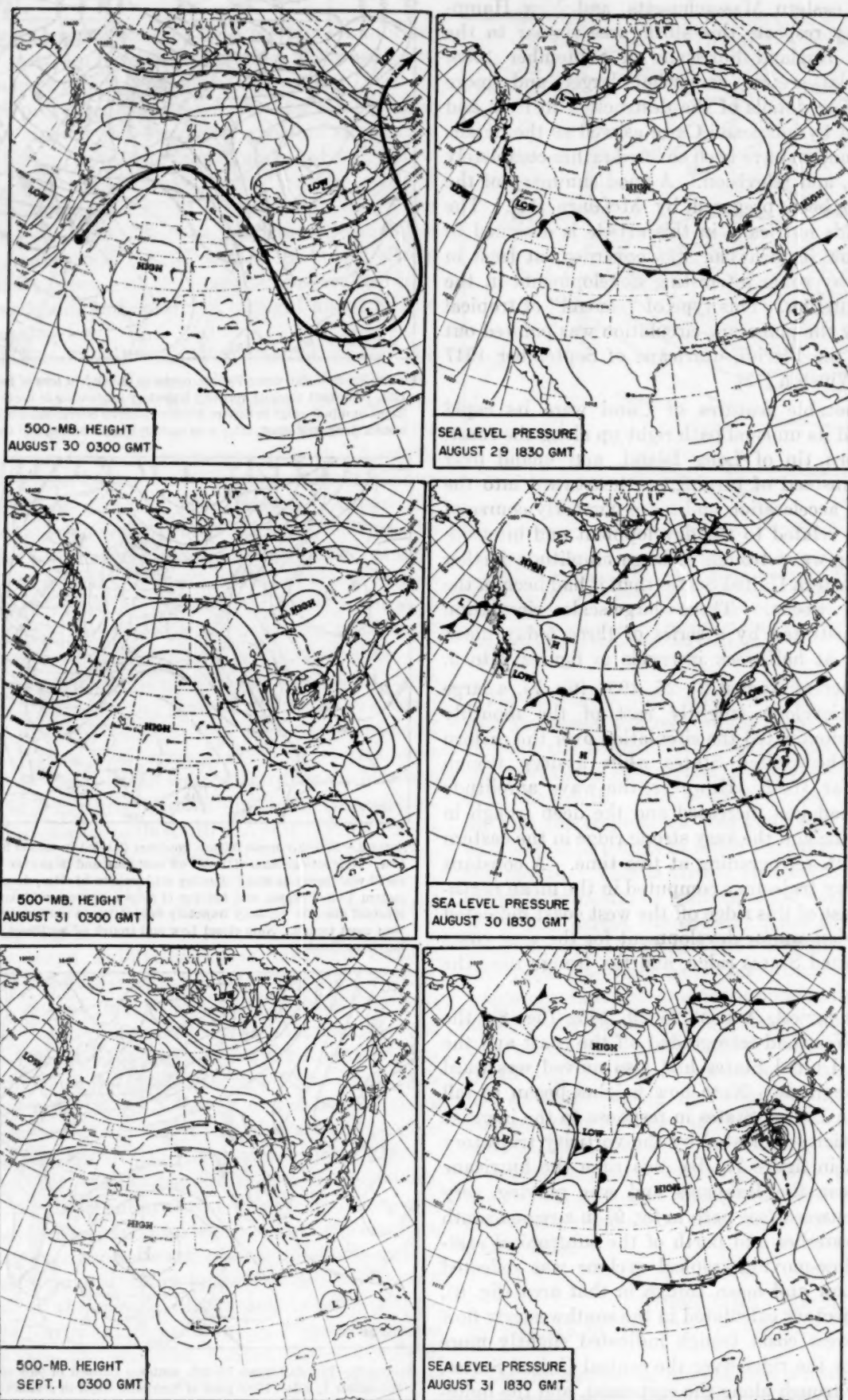


FIGURE 10.—Sequence of daily 500-mb. charts for 0300 GMT, August 30–September 1, 1954, and sea level charts for 1830 GMT, August 29–31, 1954, reproduced from *Daily Weather Map*. Track of hurricane Carol has been superimposed on sea level maps for August 30 and 31 with dots showing previous and subsequent 12-hourly positions relative to the 1830 GMT chart. Vorticity trajectory on 500-mb. chart for 0300 GMT, August 30, which is based on computation from spatially smoothed 500-mb. chart for this date, indicates continuing development of trough over eastern United States. Development of closed Low at 500 mb. over Lower Lakes and southerly components of flow to its east by 0300 GMT, August 31, indicate accelerating northward motion of hurricane close to or over east coast.

to continue, the tropical storm would soon come under the influence of a strong southwesterly current to the east of a newly developed long-wave trough of large amplitude over the eastern United States.

The next chart for August 28–September 1, 1954, covers the period during which the hurricane made its rapid trip up the east coast and across eastern New England (fig. 9). The path of the storm between August 28 and September 1 lay just to the east of and generally parallel to the newly established mean trough along the east coast. Note how the changes in circulation indicated by the vorticity trajectory of figure 8 generally worked out—viz, the continental ridge retrograding farther in the United States, the trough developing along the east coast, and a ridge also developing in the western Atlantic south of Newfoundland. There is little doubt that these straightforward developments in the 5-day mean wave pattern at middle latitudes, as illustrated in figures 7–9, were of primary importance in the life history of Carol following its initial stages of development near the Bahamas.

A more detailed history of Carol in relation to the upper-level wave pattern is given by the 3-day sequences of sea level and 500-mb. charts in figure 10. These charts are reproductions of printed maps appearing on the *Daily Weather Map*, and it should be noted that the 500-mb. charts are for a time  $8\frac{1}{2}$  hours later than the sea level charts. The track of the hurricane has been traced on the sea level charts for the 30th and 31st showing previous and subsequent 12-hourly positions.

On the 500-mb. chart for 0300 GMT, August 30, a vorticity trajectory has been superimposed to illustrate the continuing tendency for increasing trough development along the east coast as a result of vorticity flux from upstream. This trajectory was computed from a spatially smoothed 500-mb. flow field (for the same time) which is prepared routinely by the WBAN Analysis Center. This spatial smoothing technique was introduced by Fjørtoft [13] as part of his graphical method of numerical prediction.

Perhaps of greatest importance in forcing the storm to turn northward through New England was the manner in which the indicated trough development took place over the East. Inspection of the charts with the concepts of vorticity advection in mind leads one to conclude qualitatively that a region of strong cyclonic relative vorticity (made up of both strong cyclonic shear and cyclonic curvature) near Lake Superior on the 30th was advected southeastward to form the Low over the Lower Lakes on the 31st. Also of importance in bringing about the closing-off of this Low center was the rather pronounced cresting of anticyclonic vorticity north of the Low in eastern Canada. Notable too was the fact that the ridge off the Atlantic coast built up almost simultaneously with the deepening of the Low over the Lower Lakes so that by 0300 GMT, August 31, strong southerly flow existed north of the hurricane center over the Northeast. With a deepening and slowly moving upper Low over the Lakes and the associated sea level center moving slowly eastward

across western New York, it would not be unexpected that a cyclone advancing up the east coast would accelerate rapidly and stay very close to the coast or even be steered inland. In fact, it is worth pointing out that in many of its basic features (i. e., intensification of a planetary trough, development of a deep upper-level cyclone center west of the Appalachians, and anticyclonic circulation cresting across the top of the Low through southeastern Canada) this situation was rather similar to several cases of recent years in which intense extratropical storms turned inland along the east coast (e. g., [14, 15]). Since some of these storms have been predicted rather well by numerical prediction methods [16], it is quite possible that numerical methods could be successfully applied in this case. It is understood that more detailed investigations of hurricane Carol are currently being pursued.

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# THE SUCCESSIVE PRESSURE JUMP LINES OF AUGUST 16, 1954<sup>1</sup>

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## INTRODUCTION

Two pressure jump lines moved across Washington, D. C., one after the other, within 35 minutes on August 16, 1954. The first line passed the Central Office of the Weather Bureau at 1842 EST and the second one at 1917 EST. Both pressure jump lines were traced back to western Pennsylvania where they apparently originated. Violent weather accompanied the lines from western Pennsylvania through Maryland, northern Virginia, and Delaware. Hail, strong winds, and heavy rain caused much damage in the Pittsburgh area of Pennsylvania. An unconfirmed tornado was reported near Martinsburg, W. Va., and funnels aloft were observed near Leesburg, Va. [1]. Strong winds and heavy rain were reported at several stations in the path of the two pressure jump lines which moved from Pennsylvania south-southeastward into southern Virginia and North Carolina. In this study the unusual twin system of pressure jump lines is documented and the relation of the series of severe storms to the lines is shown.

## SYNOPTIC SITUATION

At 1330 EST a cold front was carried by WBAN Analysis Center extending southwestward from just north of the State of Maine to the extreme southeastern corner of Michigan. From there the front took a more west-southwestward trend, passing through extreme northern Indiana to northwestern Kansas, where it curved north-westward, becoming stationary through northeastern Wyoming and central Montana on into Canada.

The surface winds over the North Atlantic States were predominantly from the west.

A squall line, carried on the map at this time, was oriented northeast through southwest, extending from eastern Lake Erie to north-central Kentucky. The northern tip of this line was carried about 50 miles ahead of the cold front and the southern edge about 400 miles in advance of it.

Six hours later, at 1930 EST (fig. 1), the cold front had advanced southeastward about 200 miles and extended from southern Maine southwestward across New York and northwestern Pennsylvania and westward across Ohio. A squall line was carried about 40 miles southeast of Washington, D. C.

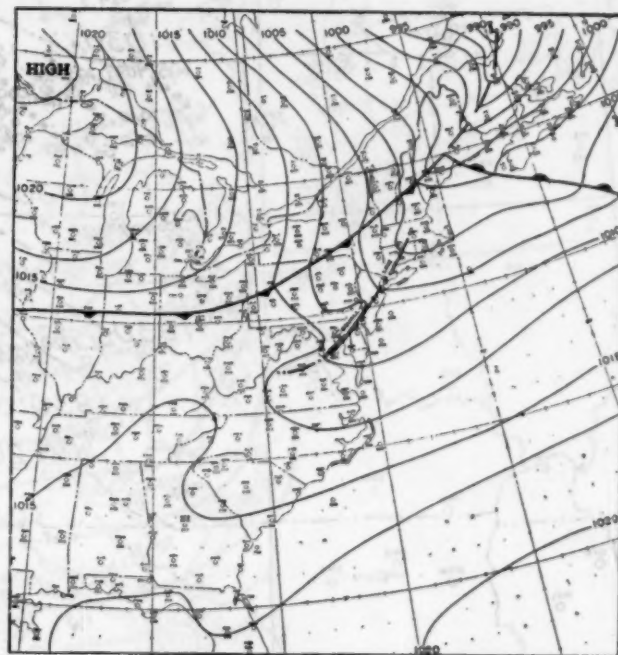


FIGURE 1.—Surface chart, 1930 EST, August 16, 1954.

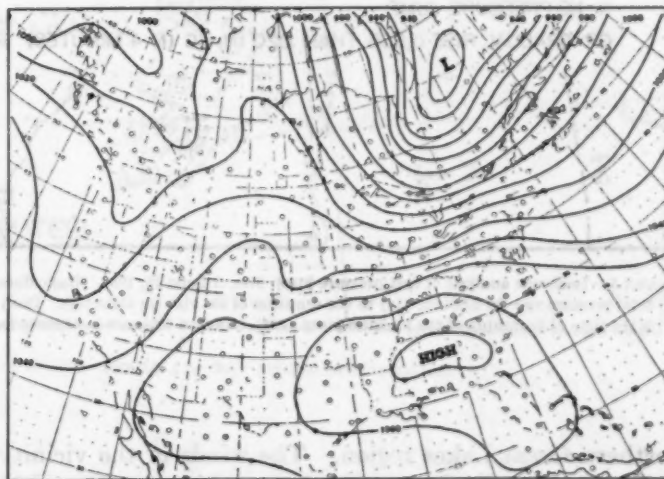


FIGURE 2.—700-mb. chart, 1000 EST, August 16, 1954.

On the 1000 EST 700-mb. analysis, a low pressure system was centered over northern Quebec Province and a high pressure system was situated over northern Alabama. (See fig. 2.) A trough line extended from the southwestern corner of Minnesota southwestward through central Nebraska into northwestern Kansas. The maximum winds were westerly between 40 and 50 knots over the

<sup>1</sup> The research reported on in this paper has been in part sponsored by the Geophysics Research Directorate of the Air Force Cambridge Research Center, Air Research and Development Command.

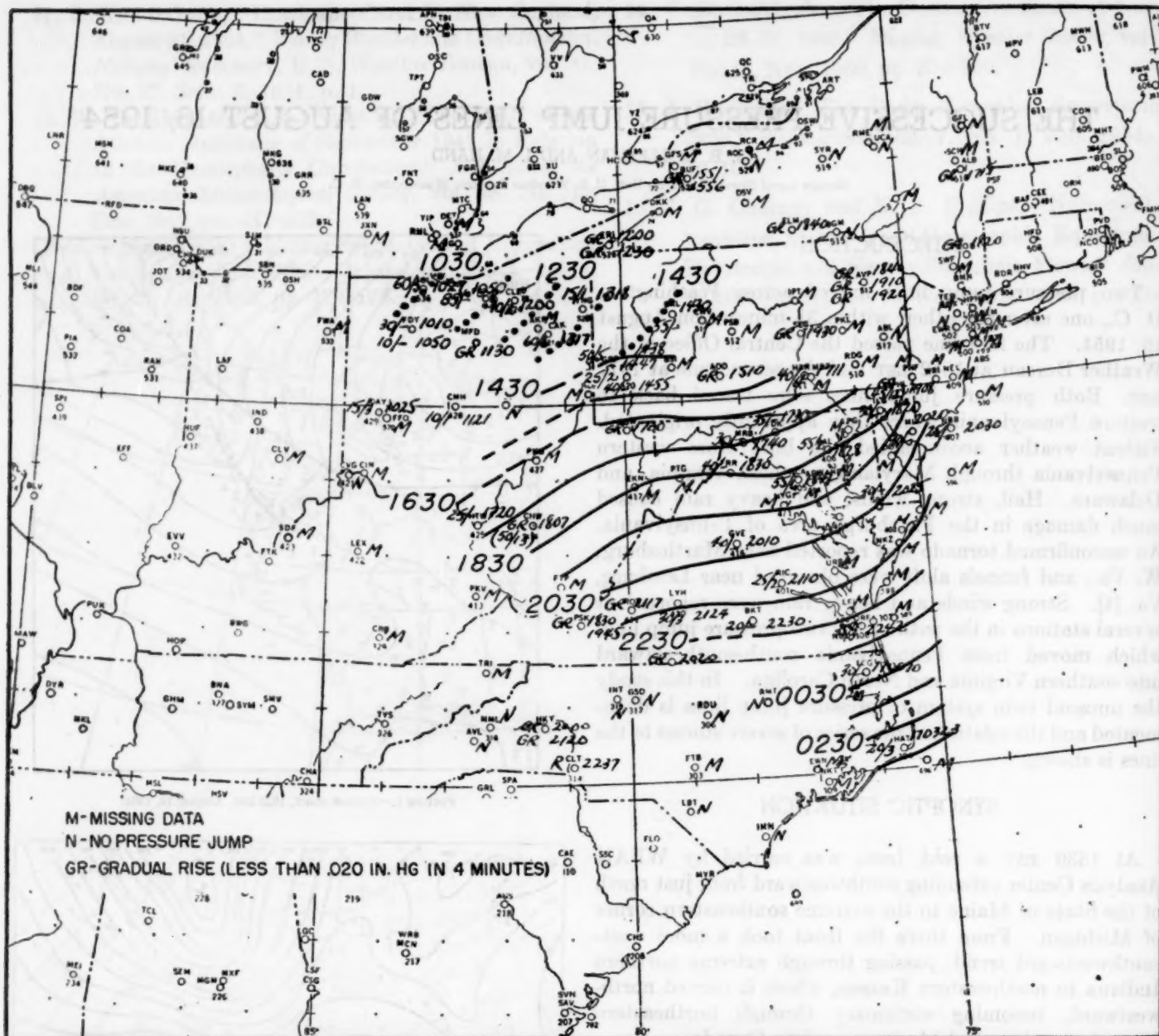


FIGURE 3.—Isochrone analysis of first pressure jump line, August 16, 1954. Basic data taken from microbarograms are indicated. To left of station circle is given the ratio of the total pressure rise (in 0.001 in. Hg) to the duration of the rise (in minutes). Dash for duration of rise means reading was from a 4-day trace. To the right of the station circle is the time of beginning of the pressure jump (EST). Dotted lines are isochrones for pressure jump line from west.

northern Great Lakes region. The winds in the vicinity of Washington, D. C., at 700 mb. were between 25 and 30 knots from the west-northwest.

On the 700-mb. chart at 2200 EST, the low center had moved to extreme northeastern Quebec and the High had moved southward into central Alabama. The main jet was through upper New York State and New England, but a secondary jet was evident over the local area with a 60-knot wind reported at Washington.

#### ANALYSIS OF PRESSURE JUMP LINES

Two independent areas of pressure jumps existed on August 16 and these areas seemed to join in southwestern Pennsylvania. The first series of pressure jumps was reported from Iowa eastward to Pennsylvania and began during the early morning hours. The second series of jumps began in southwestern Pennsylvania during the afternoon. An analysis of the pressure jumps from avail-

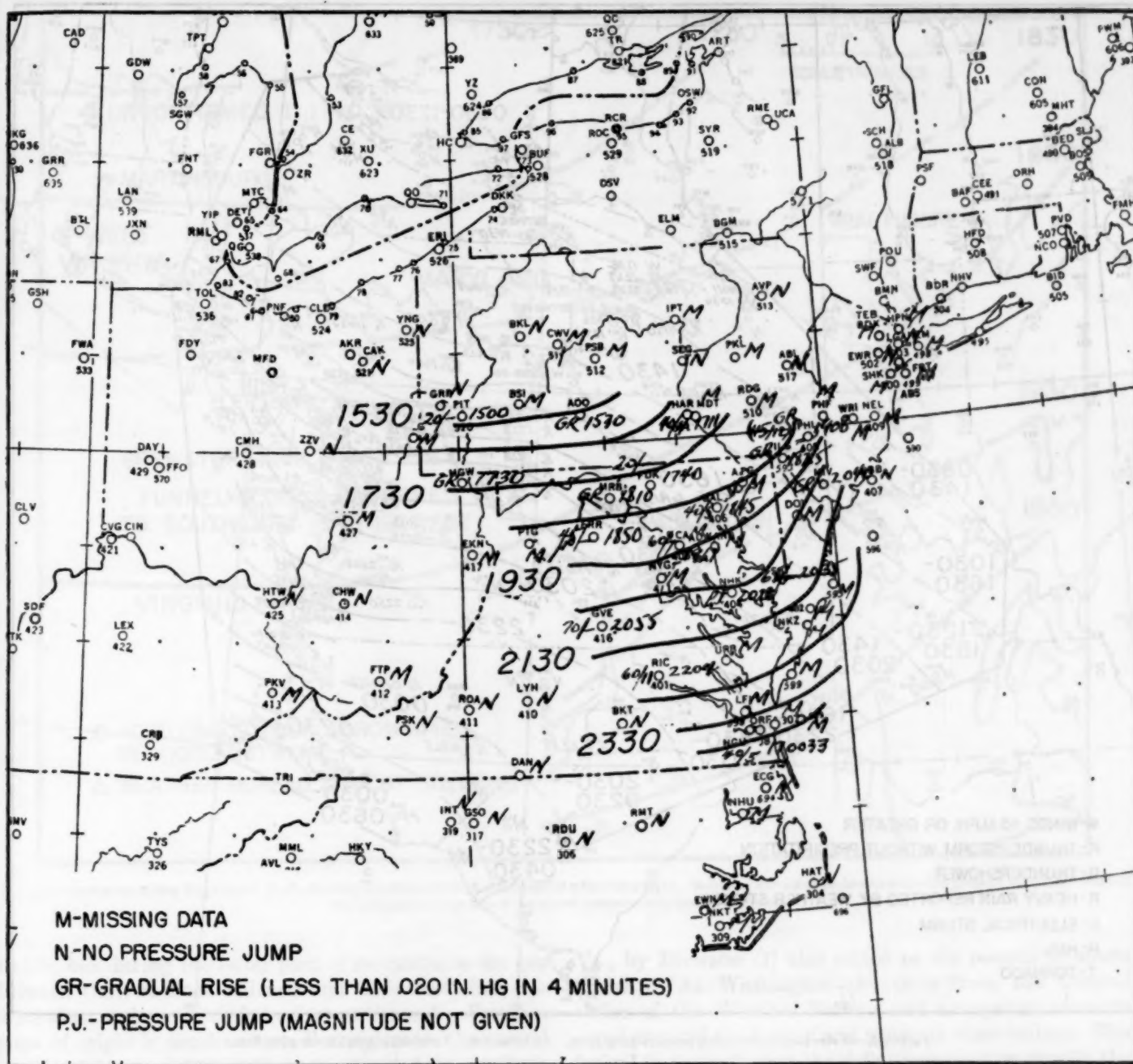


FIGURE 4.—Isochrone analysis of second pressure jump line, August 16, 1954. (See fig. 3 for description of plotting model.)

able barograms indicated a pressure jump line moving across northern Ohio into western Pennsylvania. In the latter area this line disappeared. At Pittsburgh, Pa., the existence of two pressure jumps very close to each other in time suggested that a new pressure jump line was forming in that locality at approximately 1430 EST. This new line was oriented east-northeast to west-southwest, whereas the line crossing Ohio had been oriented northeast to southwest. A careful analysis revealed no pressure jumps that would give a line oriented in the latter

direction; therefore, it was concluded that the pressure jump line from Ohio dissipated in the vicinity of Pittsburgh and Brookville, Pa., at approximately 1430 EST.

Barograph traces for stations in Pennsylvania, Maryland, West Virginia, and Virginia showed two pressure jumps occurring within an hour. Analysis revealed that two pressure jump lines actually did exist, one following the other and roughly parallel to it. These two lines are the successive pressure jump lines discussed in this study, and the pressure jump line coming from the west (repre-

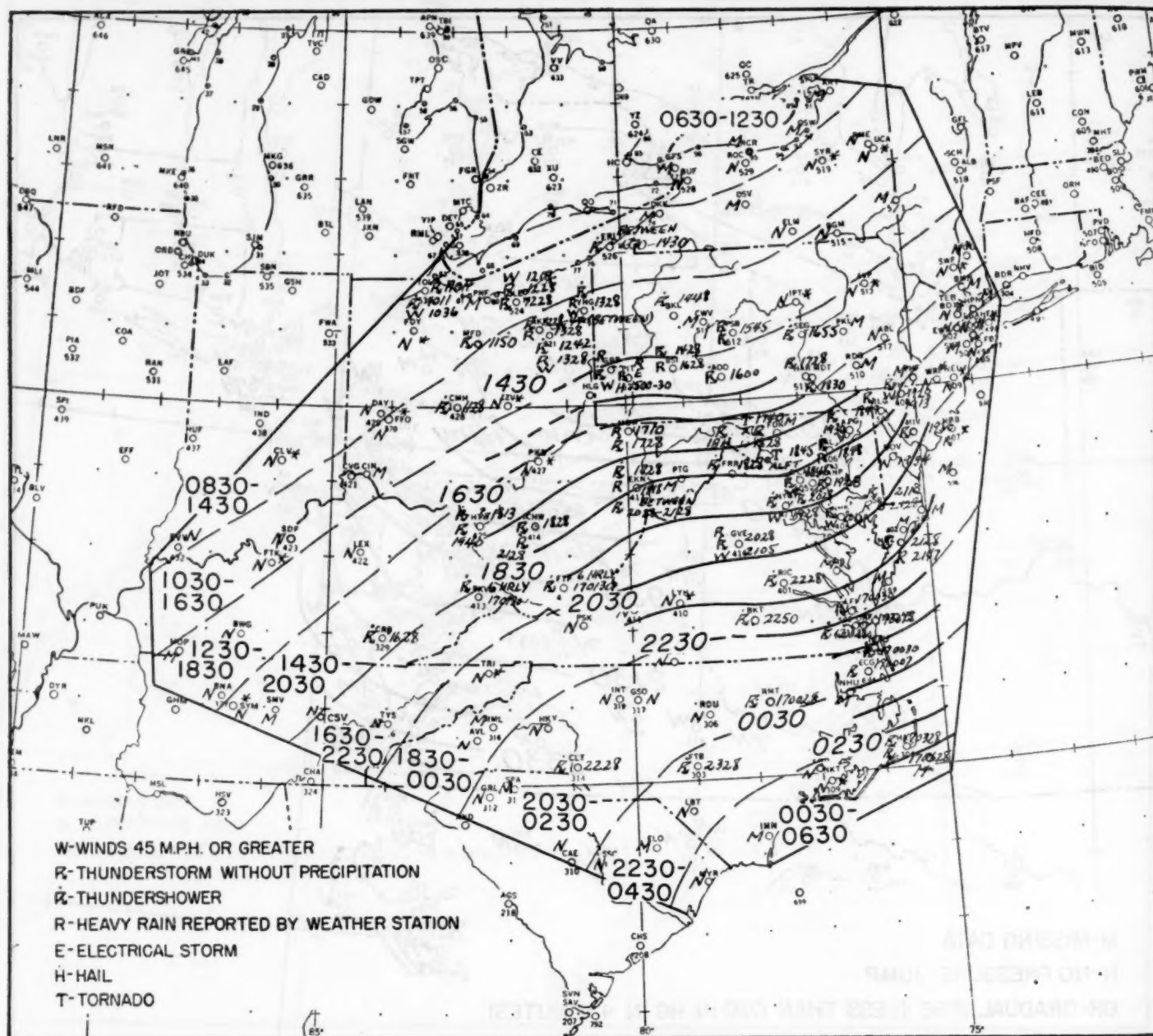


FIGURE 5.—Severe local storms along pressure jump lines. All times EST. Asterisk indicates incomplete data.

sented as a dotted line in fig. 3) is considered only in offering an explanation of the thunderstorm activity in Ohio and because of the fact that the latter line appears to have intersected the first of the two former lines in the vicinity of Pittsburgh.

Figure 3 shows the movement of the first of the pressure jump lines that originated in Pennsylvania. The first line moved from southwestern Pennsylvania to Cape Hatteras, N. C., in 13 hours (1430-0330 EST), a distance of 400 miles, giving an average speed of approximately 31 m. p. h. The width of the line (distance between ends of isochrones) was small at the beginning, approximately 120 miles. However, it grew to 340 miles at its widest point and then decreased to approximately 80 miles in width in

southern Virginia and North Carolina. Some of the isochrones in figure 3 are dashed for a part of their length because of lack of data in the area. The pressure jump line is believed to have existed in such areas for reasons of continuity, nevertheless. The southwestern part of the line did not appear until jumps at Huntington and Charleston, W. Va., occurred. There is the possibility that this may have been another pressure jump line, but there are no conclusive data to substantiate this idea; therefore, all the jumps are considered to be part of the same system.

The second pressure jump line was not quite as extensive as the first. (See fig. 4.) It followed from a few minutes to a half hour behind the first line during the first half of

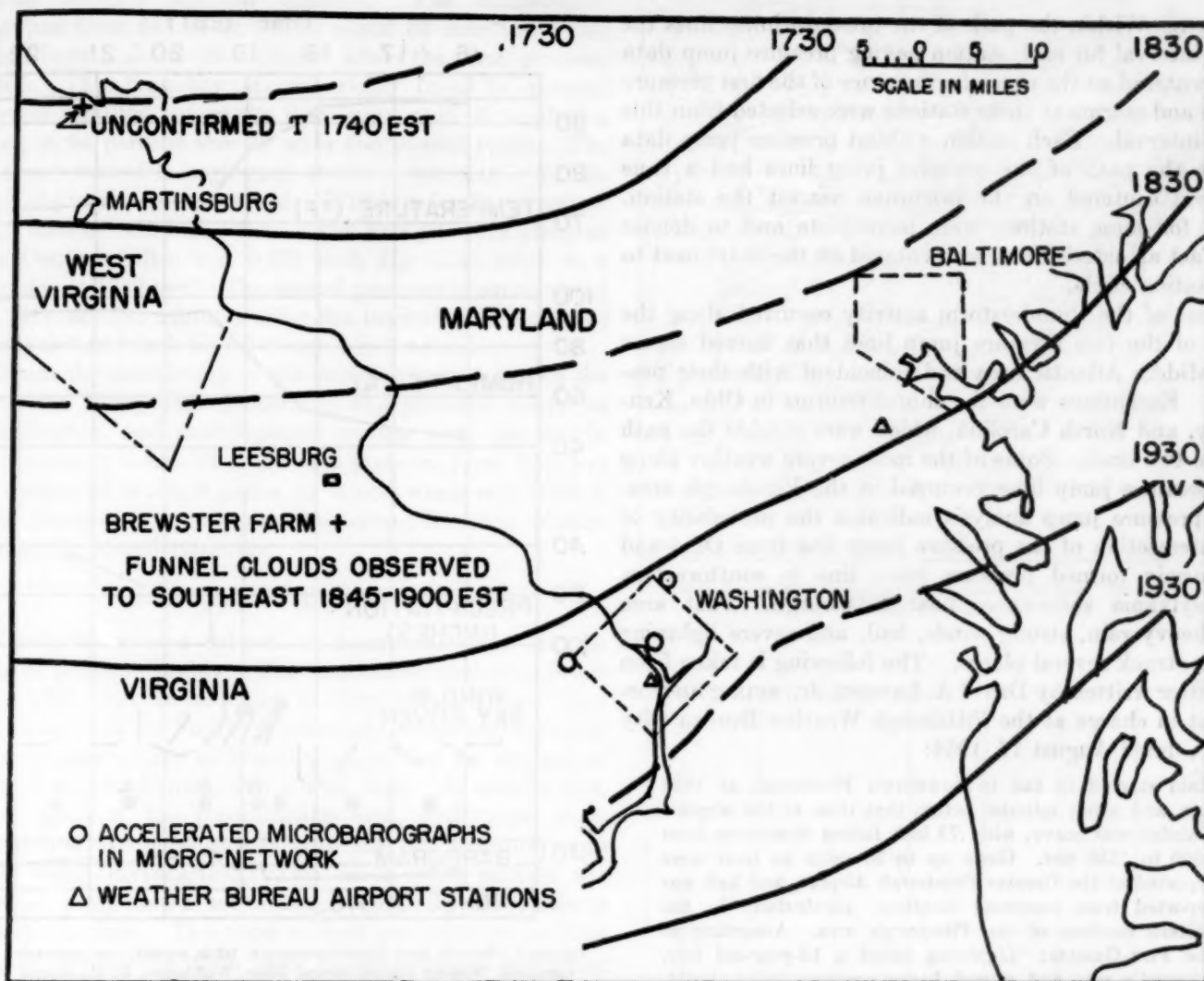


FIGURE 6.—Area surrounding Washington, D. C., showing the micro-network of accelerated microbarographs. Solid line represents isochrones of the first pressure jump line. Dashed line represents isochrones of the second pressure jump line. All times EST.

its life, but during the latter part of its existence the gap between the two lines widened and the second line was more than an hour behind the first at the end. From its place of origin in southwestern Pennsylvania, the second line, in 9 hours (1530-0030 EST), traveled to southern Virginia, a distance of 270 miles, at an approximate average speed of 30 m. p. h. At the beginning the line was 120 miles in width, but during most of its existence it was approximately 200 miles in width.

#### SEVERE STORMS

Figure 5 illustrates the thunderstorm activity that occurred along the pressure jump lines. Hourly weather sequences and synoptic observations were used for the most part to obtain reports of storms. Additional information was gained concerning the storm in the Pittsburgh area through a letter from the Weather Bureau City Office at Pittsburgh. The eyewitness account and sketches of the cloud formations observed near Leesburg,

Va., by Brewster [1] also added to the records of storm activity. At Washington the data from the Central Office of the Weather Bureau and newspaper accounts supplemented the hourly and synoptic observations. The legend in figure 5 gives the definitions used to classify the storms.

To delineate areas of thunderstorms and areas in which there was no violent weather, zones were laid out with a 6-hour time interval for each zone centered on the middle isochrone for that particular zone. The first pressure jump line that originated in southwestern Pennsylvania was used to define the zones. It was extrapolated back to Lake Erie to cover the area to the northwest outside of the path covered by this line. The zones covered a broad area on each side of the two pressure jump lines that moved from Pennsylvania and were drawn parallel to the isochrones of the first line and what were considered to be logical extensions of the isochrones. Outside the path of the two pressure jump lines, storms within the 6-hour interval as obtained from the weather sequences were

plotted. Within the path of the pressure jump lines the time interval for each station having pressure jump data was centered on the time of occurrence of the first pressure jump and storms at these stations were selected from this time interval. Each station without pressure jump data inside the path of the pressure jump lines had a time interval centered on the isochrone nearest the station. Data for some stations were incomplete and to denote this fact an asterisk has been entered on the chart next to the station circle.

Most of the thunderstorm activity occurred along the path of the two pressure jump lines that moved across the Middle Atlantic area and coincident with their passage. Exceptions were the thunderstorms in Ohio, Kentucky, and North Carolina, which were outside the path of the two lines. Some of the most severe weather along the pressure jump lines occurred in the Pittsburgh area. The pressure jump analysis indicates the probability of an intersection of the pressure jump line from Ohio and the newly formed pressure jump line in southwestern Pennsylvania somewhere near Pittsburgh. That area had heavy rain, strong winds, hail, and severe lightning which struck several places. The following is taken from the letter written by David A. Lawson, Jr., acting meteorologist in charge at the Pittsburgh Weather Bureau City Office, dated August 17, 1954:

Rain started to fall in downtown Pittsburgh at 1458 EST, and a few minutes before that time at the airport. Rainfall was heavy, with .73 inch falling downtown from 1500 to 1530 EST. Gusts up to 50 miles an hour were reported at the Greater Pittsburgh Airport, and hail was reported from scattered locations, particularly in the eastern sections of the Pittsburgh area. According to the Post-Gazette: "Lightning killed a 12-year-old boy, stunned a man and caused heavy property loss to buildings and utility lines."

As the new pressure jump line moved south-southeastward, another line formed and moved a short distance behind. Ten miles north of Martinsburg, W. Va., an unconfirmed tornado was reported at 1740 EST, about the time of the passage of the second pressure jump line. Several miles southeast on the Brewster farm near Leesburg, Va., protrusions were observed between 1845 and 1900 EST extending from a cloud which had passed the farm roughly 45 minutes before the observation [1]. Strong winds but no rain accompanied this cloud at the farm. From the description of the protrusions it is believed that they were funnels aloft. They were observed to the southeast of the Brewster farm, thus placing them between Leesburg and Washington, D. C., and on the first pressure jump line. Brewster related seeing a peculiar cloud to the northwest about an hour behind the cloud with the protrusions. This second cloud is believed to have been associated with the second line. Heavy rain showers and some wind accompanied it. Figure 6 shows the location of the Brewster farm on an enlarged map of the area surrounding Washington. Isochrones for the two pressure jump lines are entered to indicate the

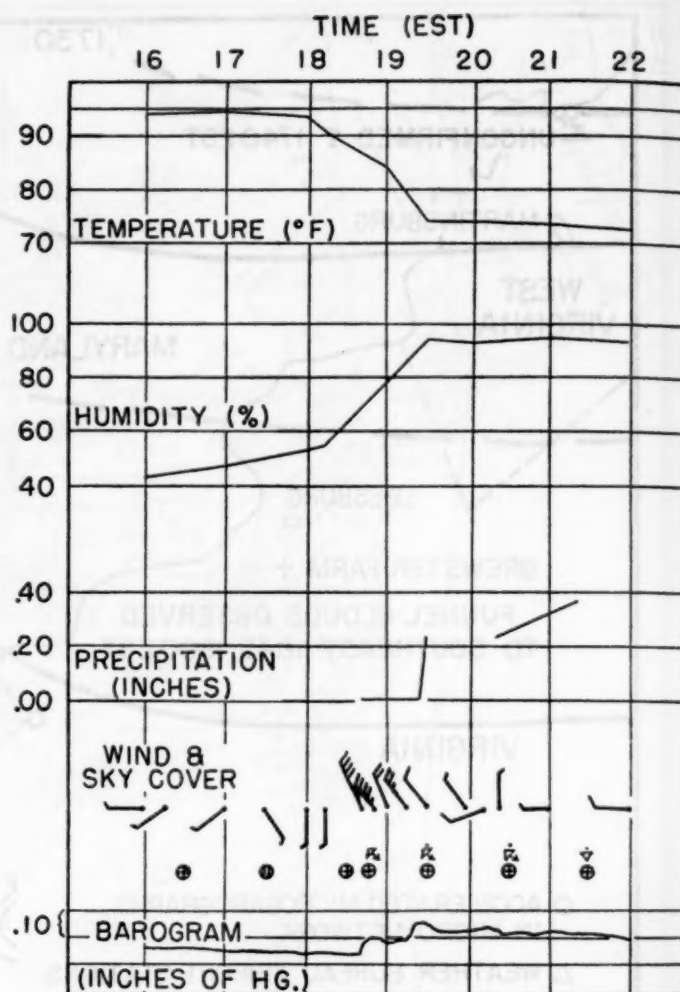


FIGURE 7.—Records from hygrothermograph, triple register, and accelerated microbarograph, Weather Bureau Central Office, Washington, D. C., August 16, 1954. Sky cover obtained from hourly sequence reports from Weather Bureau Station at National Airport.

relation of the lines to the storms which are recorded on the enlarged map. Heavy rain and strong winds were reported at many points in Maryland and northern Virginia. The weather associated with the pressure jump lines in southern Virginia and North Carolina was less violent.

When the pressure jump lines passed Washington, winds with gusts to 52 m. p. h. were observed at the Weather Bureau Station at National Airport and a thunderstorm occurred. The set of instruments at the Central Office (a hygrothermograph, a triple register for wind and precipitation, and a rain gage) along with the micro-network of three accelerated microbarographs, one of which is at the Central Office, gave a detailed picture of the weather associated with the pressure jump lines. Figure 6 illustrates the micro-network of accelerated microbarographs in the metropolitan area of Washington. With the occurrence of the first pressure jump at the Central Office, the wind shifted from south to northwest at 40 m. p. h. and 10 minutes later was 45 m. p. h. (See fig. 7.) During this time a trace of rain fell and the Na-

tional Airport reported thunder. The temperature dropped from 84° to 74° F. in about 30 minutes. This drop began about 20 minutes after the first pressure jump. The humidity started rising from 54 percent several minutes before the first jump until it reached a peak of 94 percent shortly after the second jump. The heaviest rain fell beginning about 8 minutes after the second pressure jump started. Within a 5-minute period, 0.23 inch of rain had fallen. The first pressure jump at the Central Office was 0.055 inch Hg (1.86 mb.) in 6 minutes at 1842 EST. The second pressure jump occurred at 1917 EST (35 minutes after the beginning of the first) and was 0.060 inch Hg (2.03 mb.) in 7 minutes.

From the description of the two clouds that passed the Brewster farm, data concerning the pressure jumps at Washington, and thunderstorm reports from the hourly sequences, it seems that the first pressure jump line was accompanied in many places by strong winds and little, if any, precipitation; whereas the second line was accompanied by thundershowers.

### PRECIPITATION DISTRIBUTION

Precipitation was entered on a separate chart for the area of pressure jumps. The same zones and time intervals were used as in figure 5. Precipitation data were obtained from the hourly weather sequences and synoptic observations except at Washington, where the amount of rainfall at the Central Office was used. As can be seen from figure 8, the precipitation area, with three main exceptions, coincides closely with the two pressure jump lines being investigated. Two areas exist outside the pressure jump lines in southeastern Kentucky and southern North Carolina. The third area of precipitation in Ohio blends in with the main band of precipitation extending to the Virginia coast. The precipitation area in Ohio, excluding central Ohio, can be explained as being associated with the pressure jump line that crossed that State. The cause of precipitation in central Ohio is undetermined. The precipitation in Kentucky may have been due to convective activity. A ready explanation is not available for the precipitation in North Carolina. However, in the main area of precipitation, showers occurred close to the time of the passage of the pressure jump lines.

Figure 8 shows one area of maximum precipitation and one secondary maximum. The largest amount of rain fell in the area between Blairsville, Pa., and Akron, Ohio. The secondary maximum was in the vicinity of Salisbury and Patuxent River, Md. Both areas coincide with regions in which some of the largest pressure jumps occurred. The two areas are located on the northeast side of the path of the two pressure jump lines.

### UPPER AIR DATA

Examination was made of soundings from three stations in the path of the pressure jump lines—Pittsburgh, Pa., Washington, D. C., and Norfolk, Va. The Pittsburgh

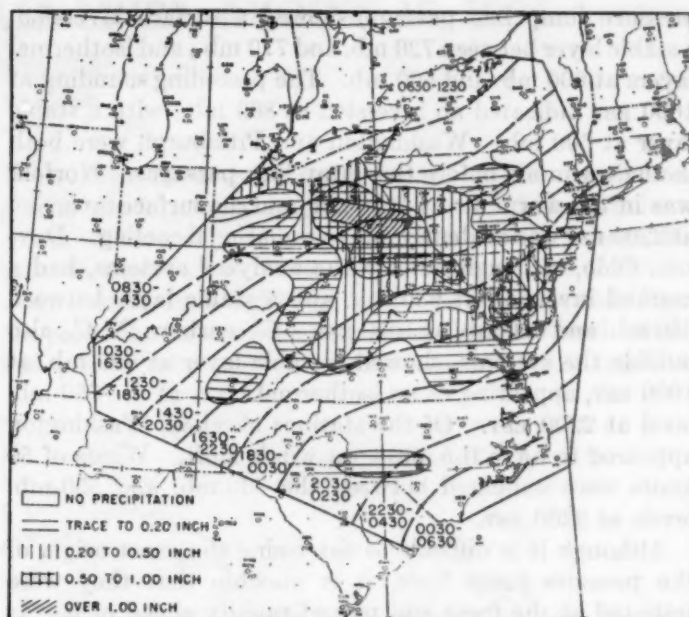


FIGURE 8.—Precipitation area along path of pressure jump lines. Precipitation in inches. Time interval in EST.

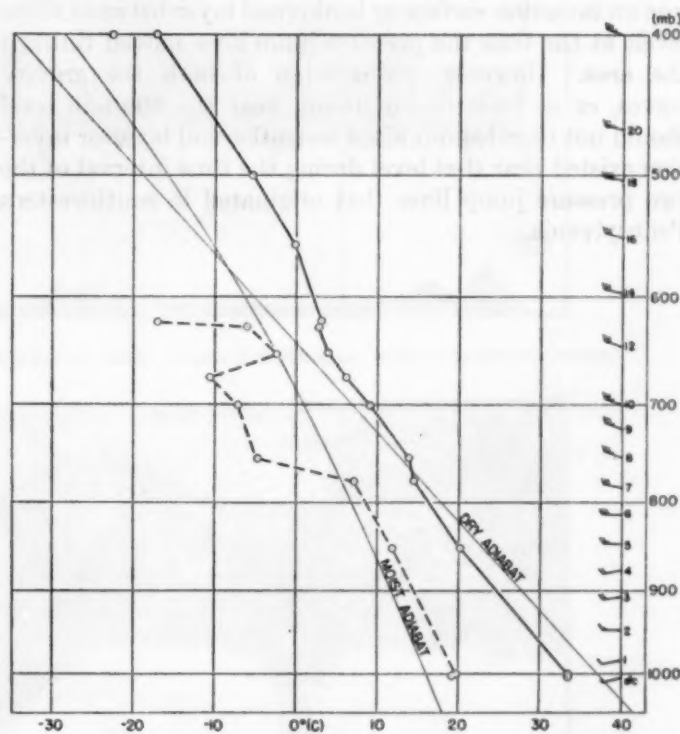


FIGURE 9.—Upper air sounding for Washington, D. C., 1600 EST, August 16, 1954. The temperature curve is represented by solid line; dew point curve by dashed line.

sounding at 1000 EST shows two inversions—one at 850 mb. and the other at 650 mb. The 1600 EST Washington sounding, figure 9, indicates an inversion at 630 mb. with a nearly isothermal layer (decrease of 0.5° C. from bottom to top of layer) between 750 mb. and 800 mb. At Norfolk the sounding at 2200 EST (less than an hour prior to the

pressure jump line passage) showed a surface inversion, a stable layer between 720 mb. and 770 mb., and isothermal layers at 600 mb. and 500 mb. The preceding sounding at 1600 EST indicated an inversion at 800 mb., with a stable layer at 600 mb. Washington and Pittsburgh were both in the warm air before the jump line passages. Norfolk was in the warm air at 1600 EST, and the surface inversion at 2200 EST was evidently due to radiational cooling. Dayton, Ohio, although outside the analyzed systems, had a marked inversion at 930 mb. and a stable layer between 650 mb. and 600 mb. at 1000 EST. Greensboro, N. C., also outside the systems, showed a stable layer at 600 mb. at 1000 EST, appearing as an isothermal layer at the 550-mb. level at 2200 EST. Of the stations checked, Washington appeared to have the strongest winds aloft. Winds of 50 knots were indicated between the 700-mb. and 550-mb. levels at 2200 EST.

Although it is difficult to determine the exact origin of the pressure jump lines, it is possible that they were initiated at the front and moved rapidly ahead of it. It is believed, from the examination of the soundings, that the gravity waves producing the pressure jumps traveled between the 850-mb. and 750-mb. levels [2], since there was an inversion surface or isothermal layer between those levels at the time the pressure jump lines moved through the area. However, propagation of both the gravity waves, or at least one of them, near the 600-mb. level should not be ruled out since an isothermal layer or inversion existed near that level during the time interval of the two pressure jump lines that originated in southwestern Pennsylvania.

### SUMMARY

Two pressure jump lines formed in southwestern Pennsylvania during the middle of the afternoon on August 16, 1954 and moved south-southeastward to North Carolina and southern Virginia during the early morning hours of August 17. The first line was followed by the second line with an average time interval of about 30 minutes. Considerable thunderstorm activity, some severe, occurred along the two lines. From available data it seems that most of the strong winds occurred with the first pressure jump line and the rain with the second pressure jump line. A pressure jump line moving across Ohio from the west is believed to have intersected the first pressure jump line near Pittsburgh, Pa. It is believed that the former pressure jump line ended in western Pennsylvania.

Two pressure jump lines that originated in Pennsylvania are believed to have been propagated at a level between 850 and 750 mb.

### ACKNOWLEDGMENTS

Helpful suggestions and assistance were given the authors by Dr. Morris Tepper and the other members of the Severe Local Storms Research Unit.

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## OBSERVATION OF TWO SQUALL LINES, AUGUST 16, 1954

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[Manuscript received September 1, 1954]

This is an eyewitness account of some interesting cloud phenomena associated with two squall lines which passed my farm on August 16, 1954. The farm is located 30 miles northwest of Washington, D. C., near Route 7 or the so-called Leesburg Pike, about  $4\frac{1}{4}$  miles south-southeast of Leesburg, Va. (See fig. 6 of the preceding article by Holleyman and Hand.)

At about 1800 EST Monday, August 16, a squall line passed the farm with strong winds and a dark turbulent cloud. There was no rain with this cloud. About 25 miles farther back to the northwest a second line of clouds with thunder and lightning could be seen approaching. No particular attention was paid to the first cloud which had passed over until about 1845 EST, when a ropelike

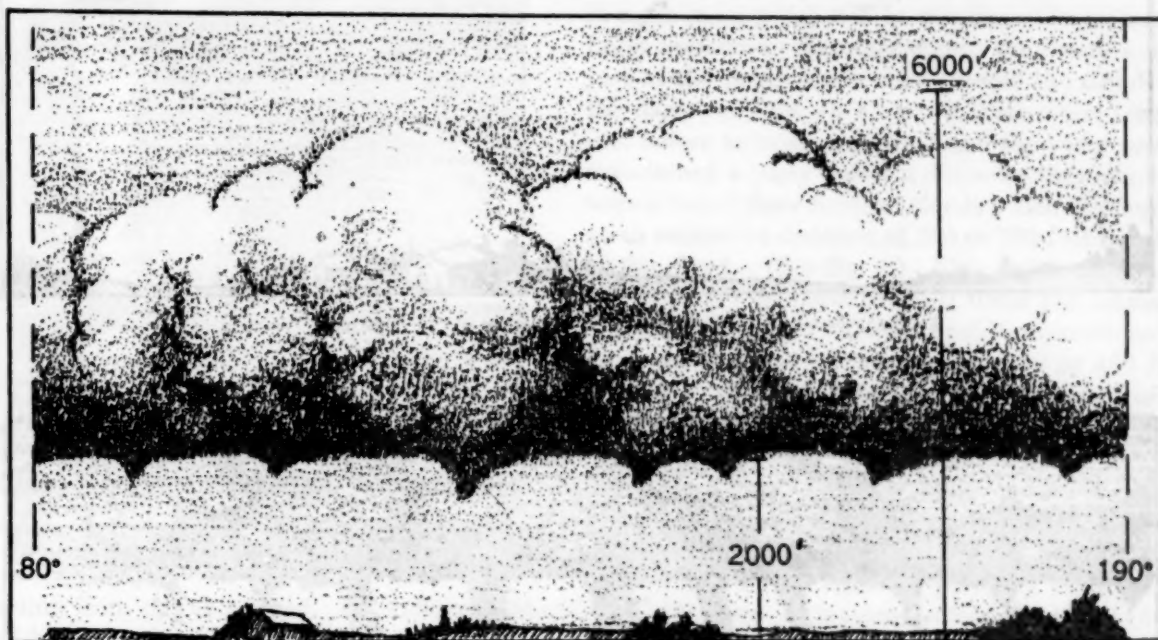


FIGURE 1.—Sketch illustrating the protrusions on the squall line to the southeast of the Brewster farm. Heights of cloud base and top above ground are estimated.



FIGURE 2.—Sketch illustrating the growth of the protrusions.

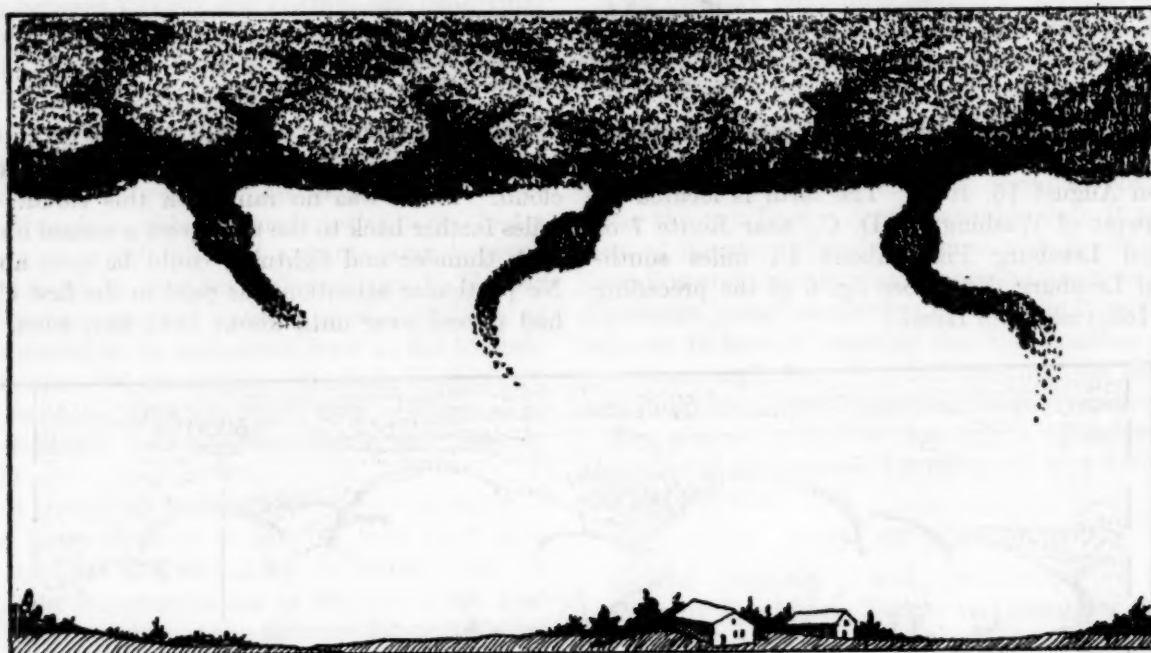


FIGURE 3.—Sketch illustrating the bulges which developed on a few of the ropelike clouds.

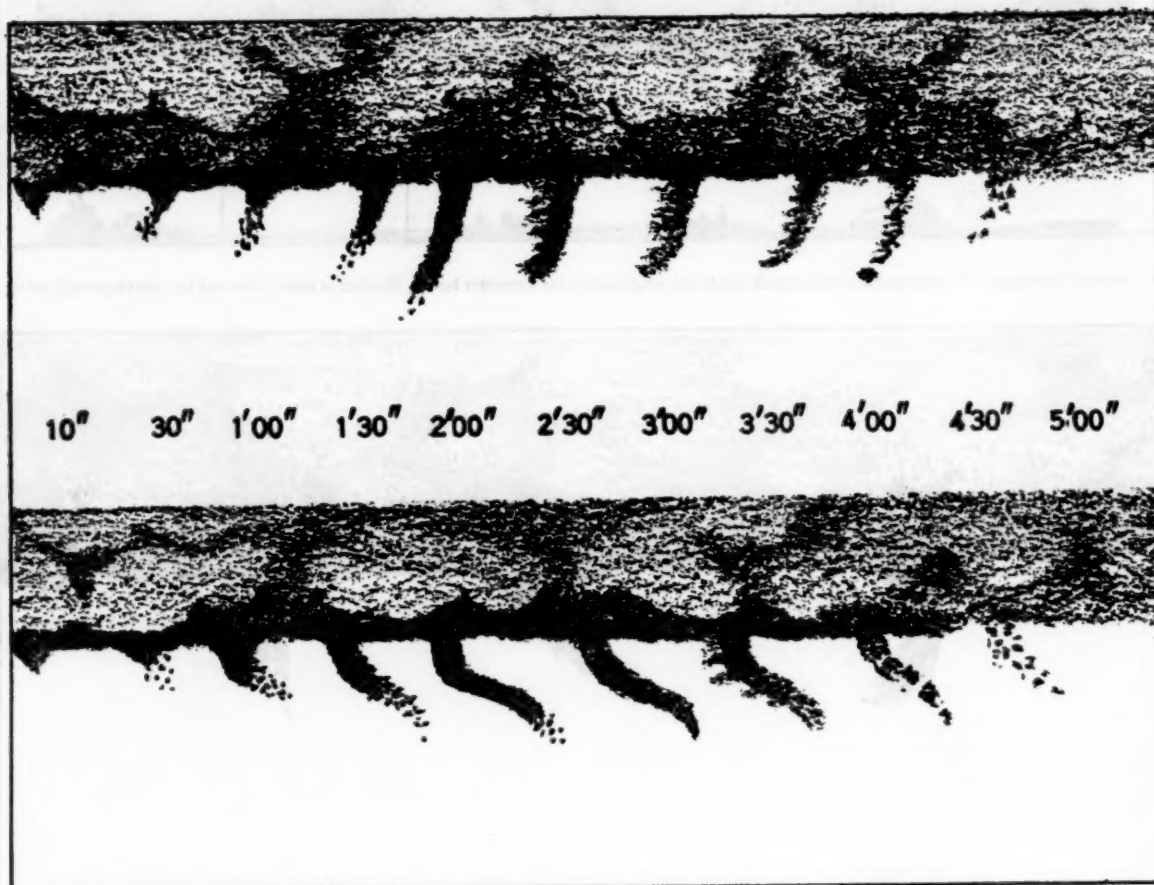


FIGURE 4.—Sketch illustrating life cycle of two typical protrusions. Estimated times are in minutes and seconds.

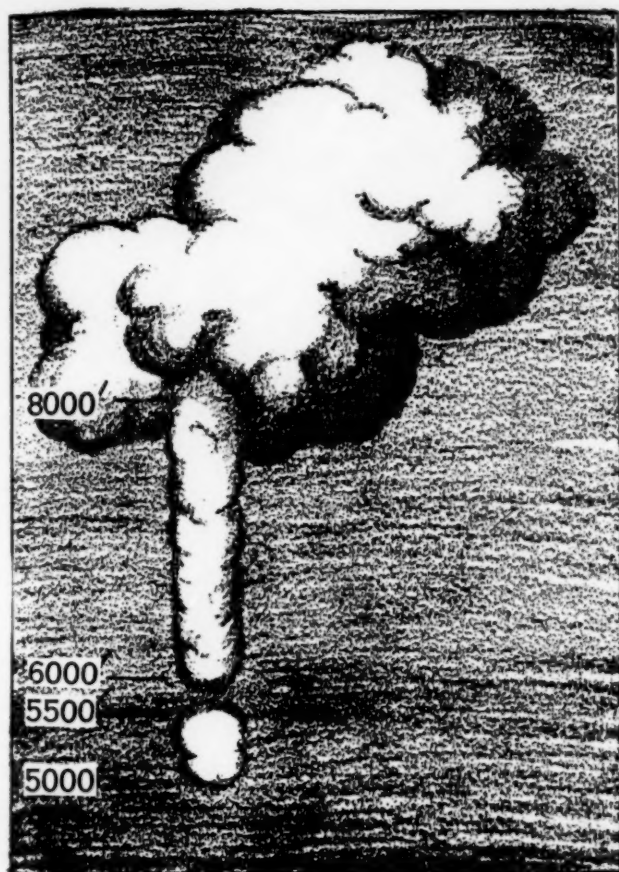


FIGURE 5.—Sketch illustrating unusual column-like formation observed northeast of the Brewster farm. Heights of different parts of formation above ground are estimated.

cloud protruding from it was noticed. At 1900 EST, the second squall line passed with some wind and heavy rain showers.

From the period 1845 to 1900 EST, the first squall line cloud was watched almost continually and at least 10 or possibly 12 ropelike appendages were seen to develop from that cloud. The cloud itself had an estimated base of 2,000 feet, with tops estimated around 6,000 feet. Since the cloud was by now from 15 to 30 miles distant and there were other buildups in the vicinity of the cloud, it could easily be the observed tops were not necessarily directly above this particular cloud. The cloud extended from about 80° to 190° in azimuth as observed from

behind. The base of the cloud was very sharp, and small protrusions developed downward southeast of the farm. These protrusions were always pointed at the bottom. (See fig. 1.)

Below a protrusion, sometimes to the right, sometimes directly below it, thin wisps of clouds would appear, gradually thickening and becoming more numerous, so that finally the ropelike appendage would be a solid mass. (See fig. 2.) In some cases, this process would continue below this cloud column, thus making it longer. The average diameter of this ropelike column was estimated to be from 300 to possibly 800 feet. The columns, except in some cases which will be mentioned later, seemed to be fairly uniform in diameter except they were a little wider just at the point where they entered the cloud. That is, the narrower ones were narrow their entire length except just before entering the cloud and the wider ones likewise maintained a fairly uniform diameter throughout. There were a few of these ropelike clouds which developed a bulge at an estimated distance of 200 or 300 feet below the base of the cloud. (See fig. 3.) This bulge extended so that its diameter was perhaps three times the diameter of the original formation. These ropelike formations extended downward an average of possibly 700 or 800 feet. The bottom of each could be seen except in two or three instances where trees blocked the horizon.

After the ropelike cloud formation had been in existence for about 3 minutes, a few wisps of clouds could be seen breaking away from the column, after which there was a rapid dissipation of the column and the base of the large squall cloud would again be perfectly straight. The life cycle of these formations averaged about 5 minutes. Rotation could not be discerned in any of the formations. Figure 4 shows the life cycle of two typical formations.

At one time (about 1900 EST) just before the second line arrived overhead and the heavy rain started, an unusual columnlike formation was observed to the northeast. Near the side of one of the towering cumulo-nimbus clouds from about 8,000 feet down to 6,000 feet was a white cloud column perhaps 500 feet in diameter with an isolated cloud not any wider than the column and about 500 feet below it. (See fig. 5.) After 3 or 4 minutes this column faded and disappeared and the isolated cloud likewise dissipated.

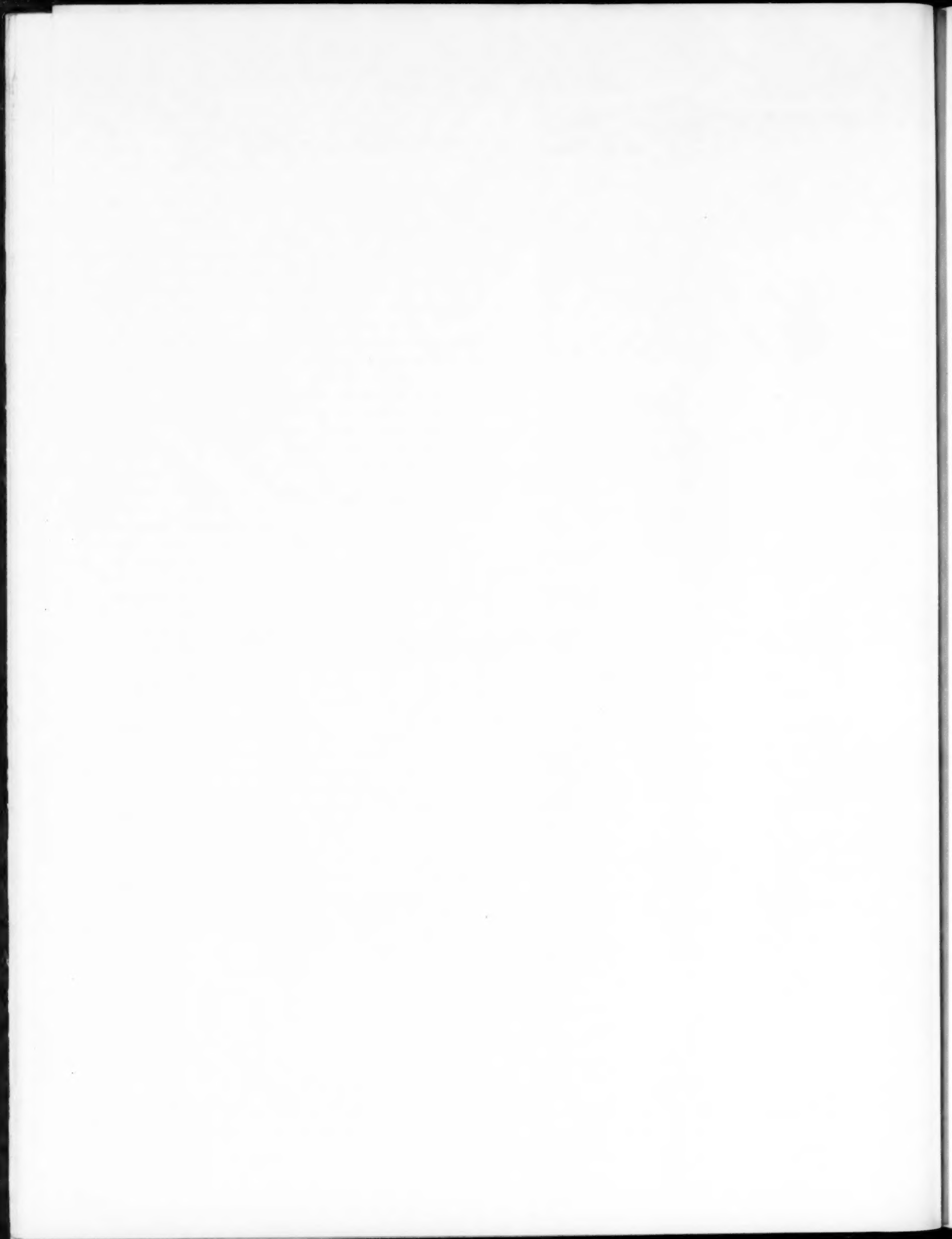
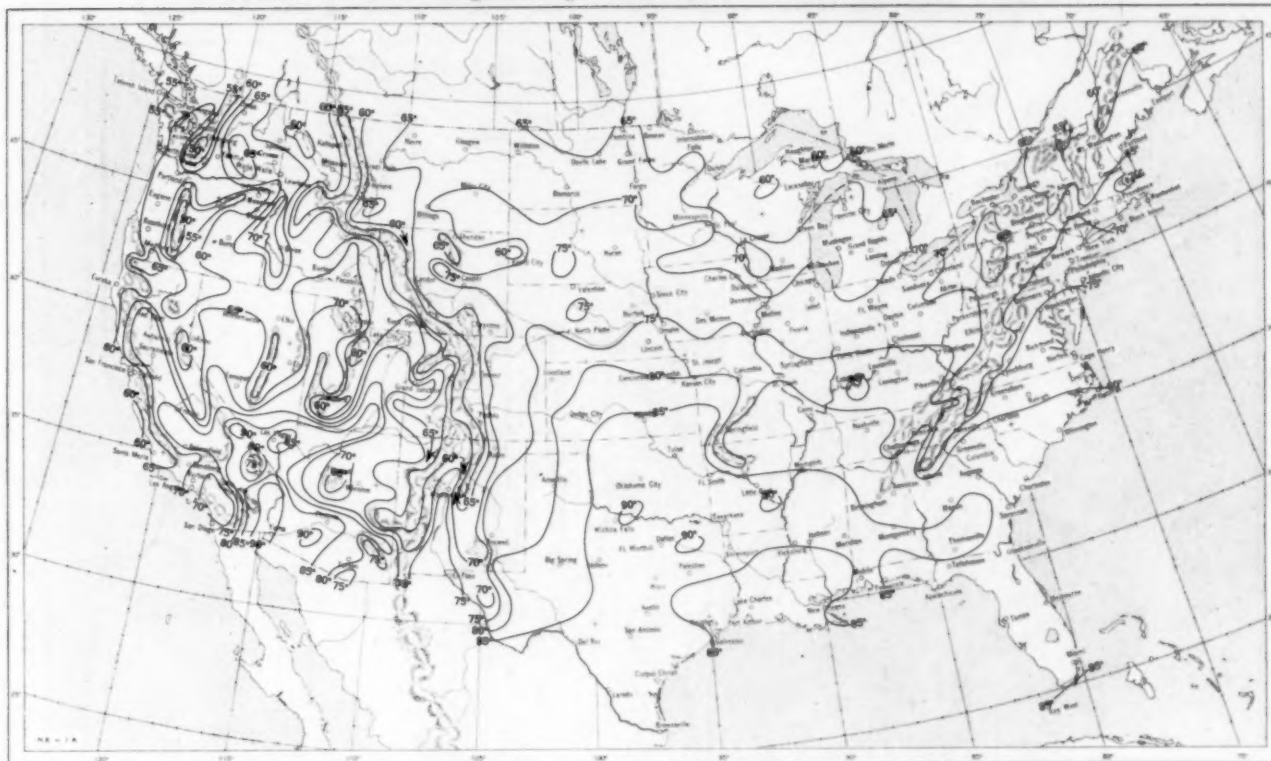
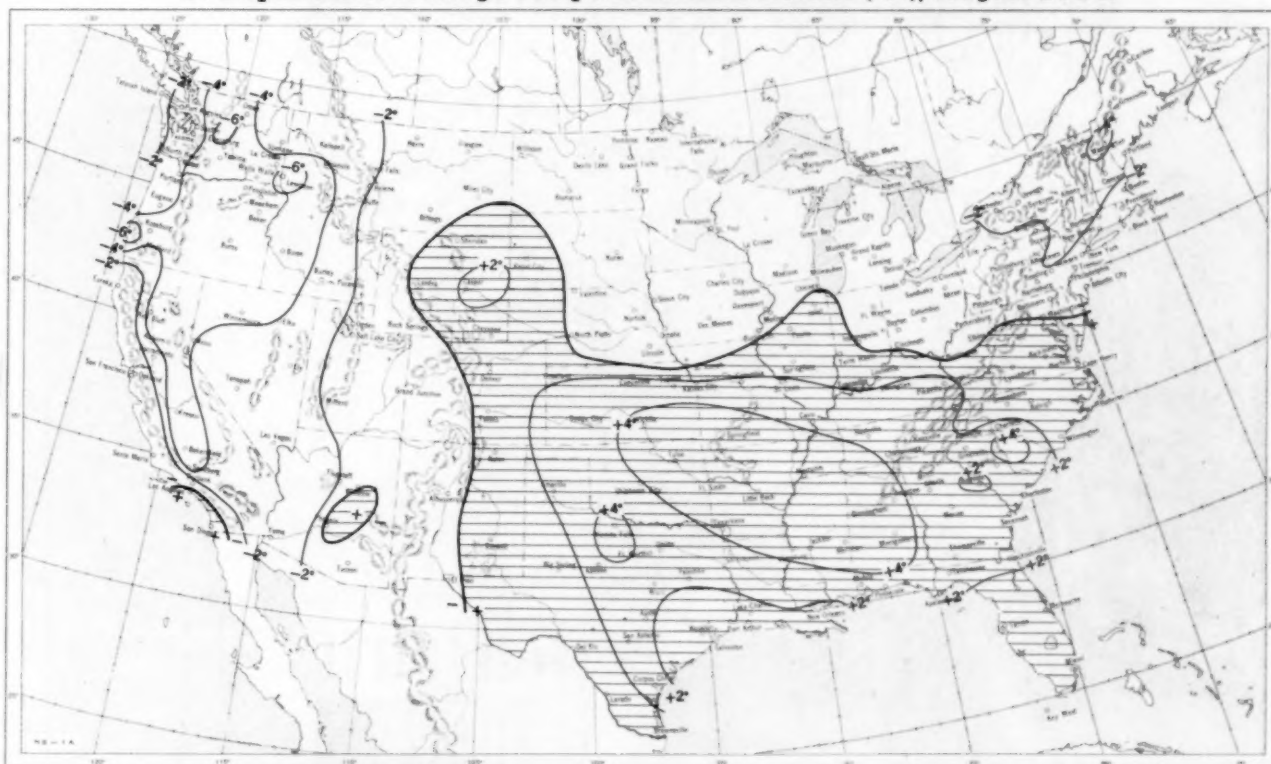


Chart I. A. Average Temperature ( $^{\circ}\text{F.}$ ) at Surface, August 1954.B. Departure of Average Temperature from Normal ( $^{\circ}\text{F.}$ ), August 1954.

A. Based on reports from 800 Weather Bureau and cooperative stations. The monthly average is half the sum of the monthly average maximum and monthly average minimum, which are the average of the daily maxima and daily minima, respectively.

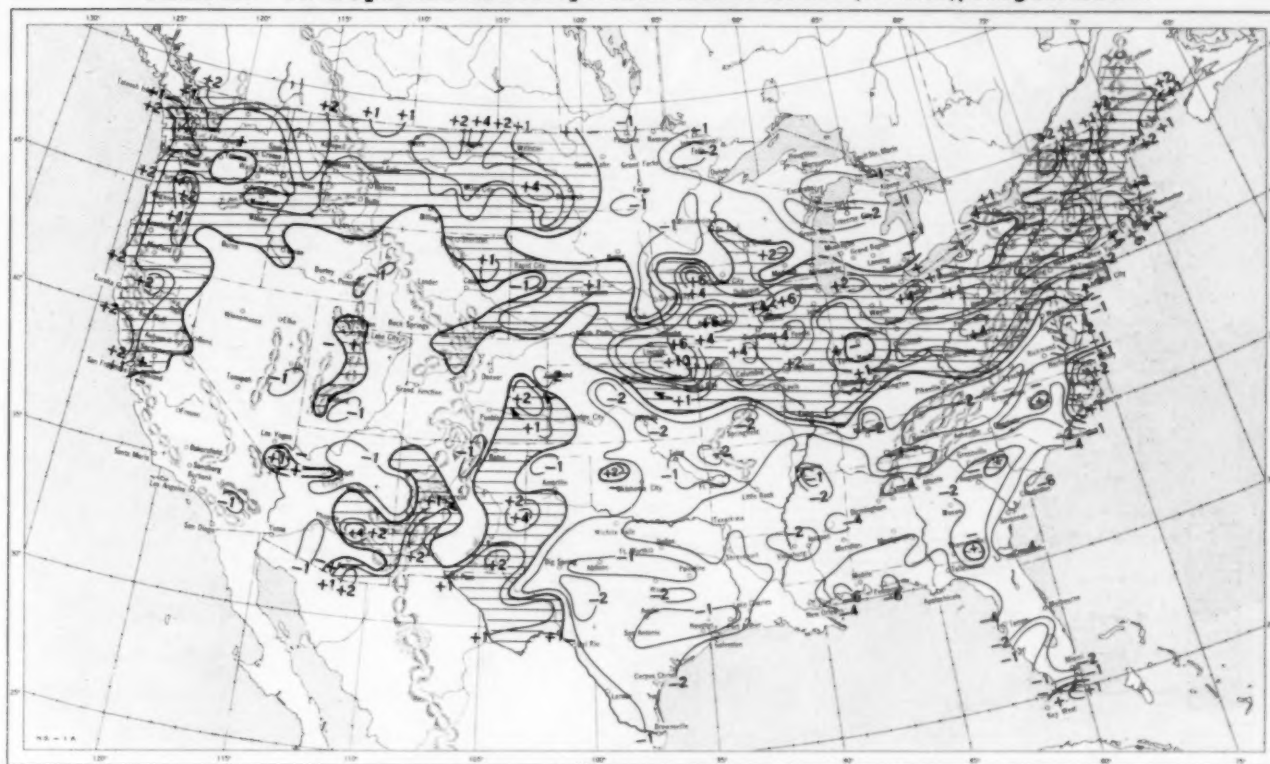
B. Normal average monthly temperatures are computed for Weather Bureau stations having at least 10 years of record.

Chart II. Total Precipitation (Inches), August 1954.

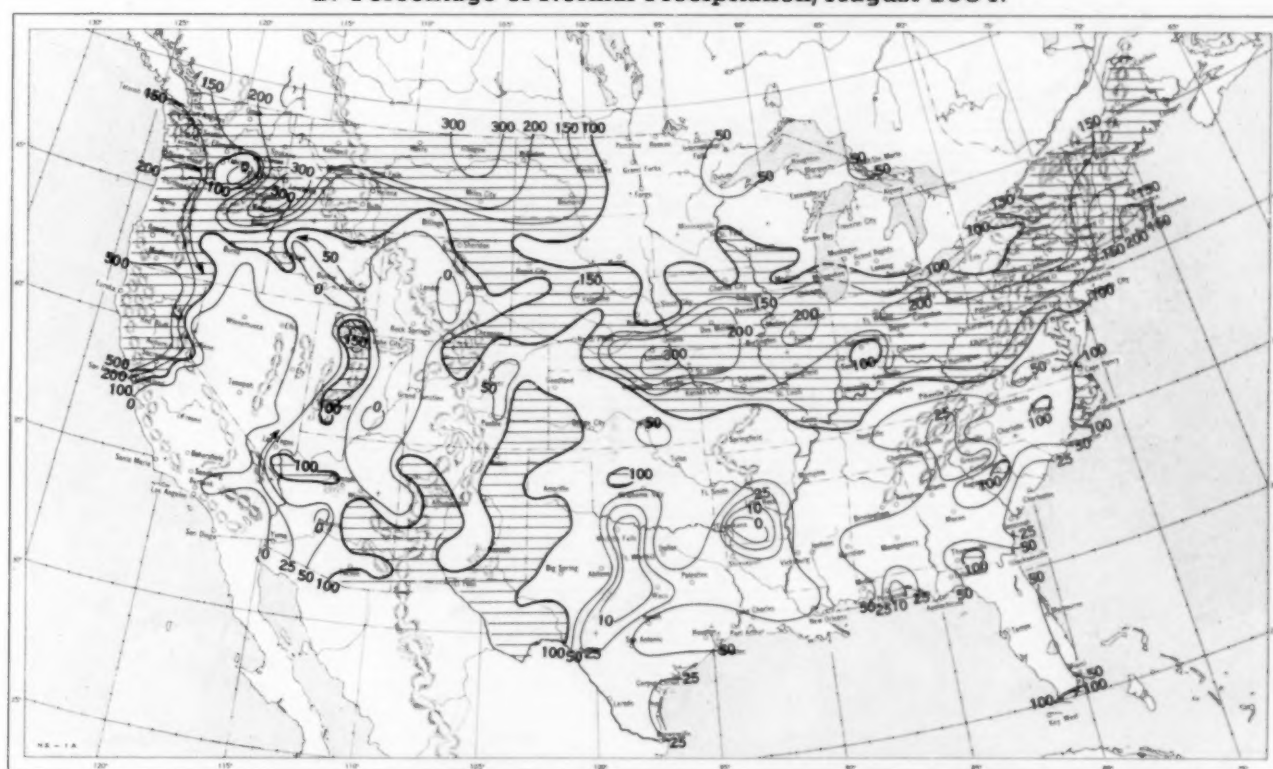


Based on daily precipitation records at 800 Weather Bureau and cooperative stations.

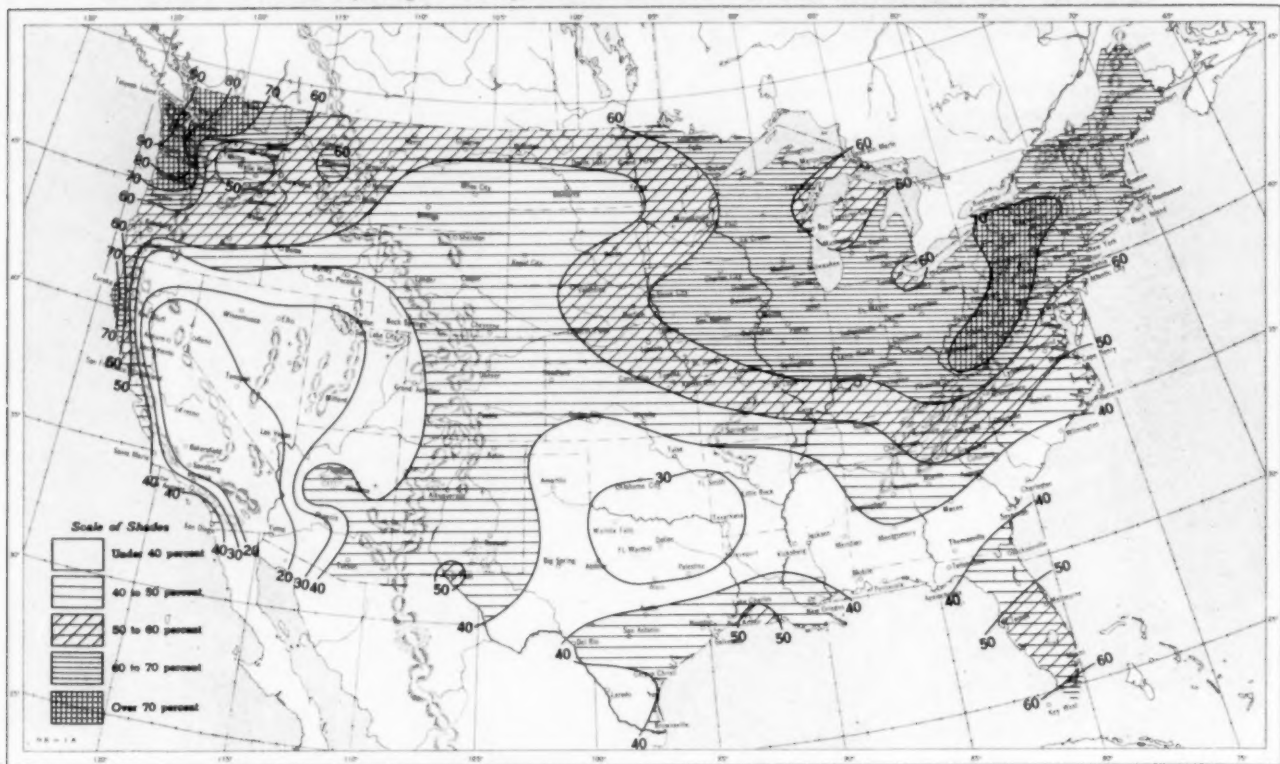
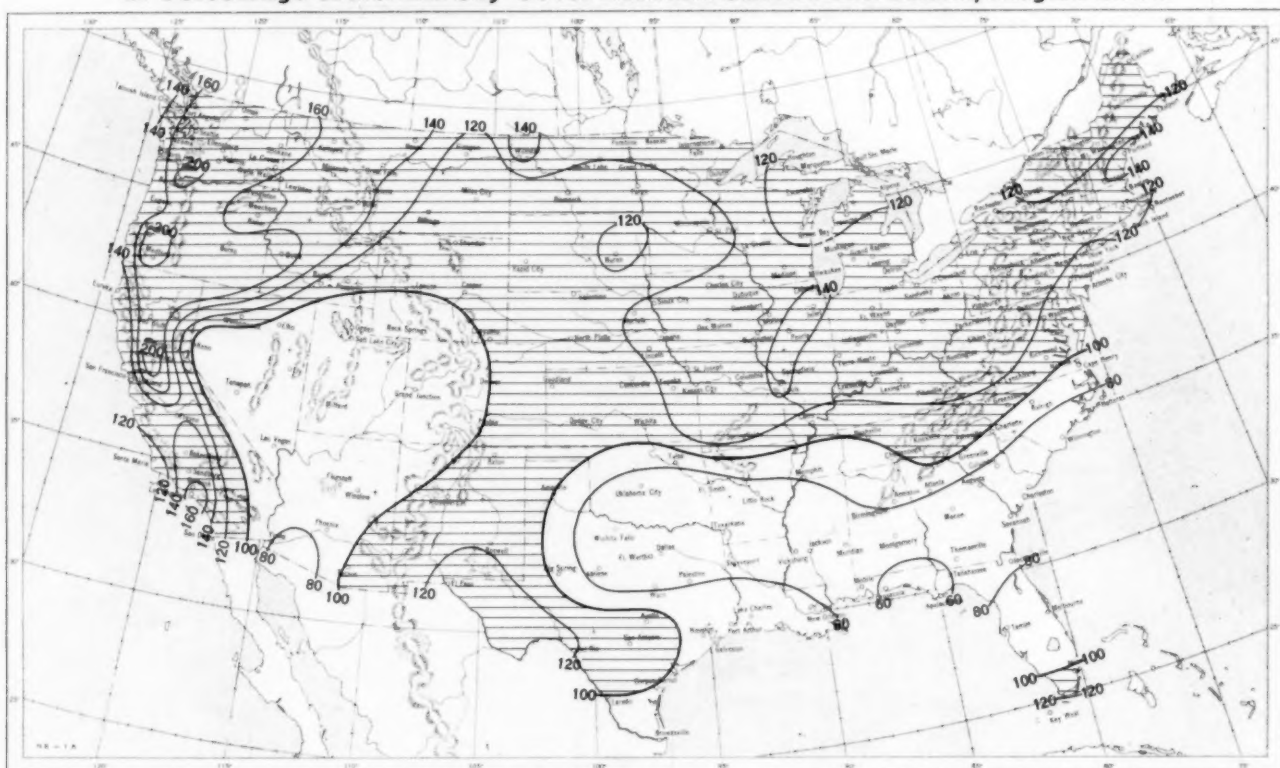
Chart III. A. Departure of Precipitation from Normal (Inches), August 1954.



B. Percentage of Normal Precipitation, August 1954.

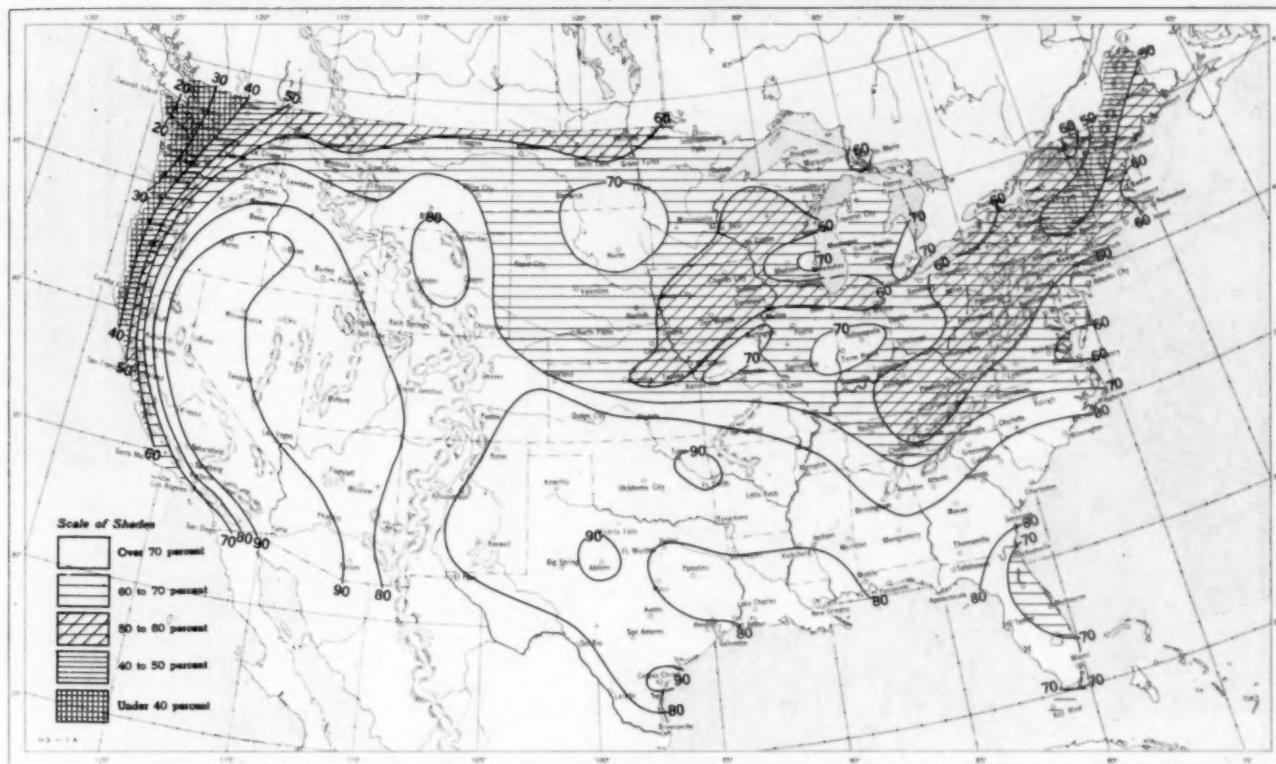


Normal monthly precipitation amounts are computed for stations having at least 10 years of record.

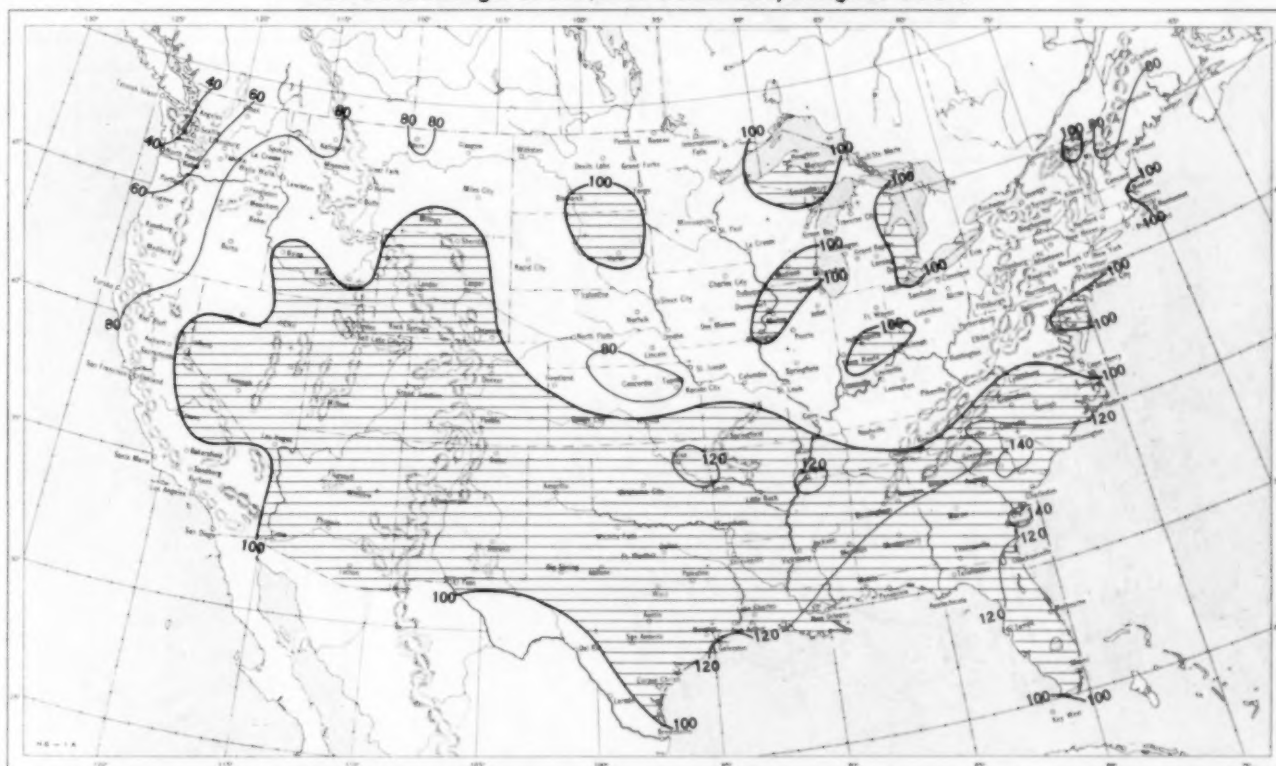
**Chart VI. A. Percentage of Sky Cover Between Sunrise and Sunset, August 1954.****B. Percentage of Normal Sky Cover Between Sunrise and Sunset, August 1954.**

A. In addition to cloudiness, sky cover includes obscuration of the sky by fog, smoke, snow, etc. Chart based on visual observations made hourly at Weather Bureau stations and averaged over the month. B. Computations of normal amount of sky cover are made for stations having at least 10 years of record.

Chart VII. A. Percentage of Possible Sunshine, August 1954.



B. Percentage of Normal Sunshine, August 1954.



A. Computed from total number of hours of observed sunshine in relation to total number of possible hours of sunshine during month. B. Normals are computed for stations having at least 10 years of record.

Chart VIII. Average Daily Values of Solar Radiation, Direct + Diffuse, August 1954. Inset: Percentage of Normal Average Daily Solar Radiation, August 1954.

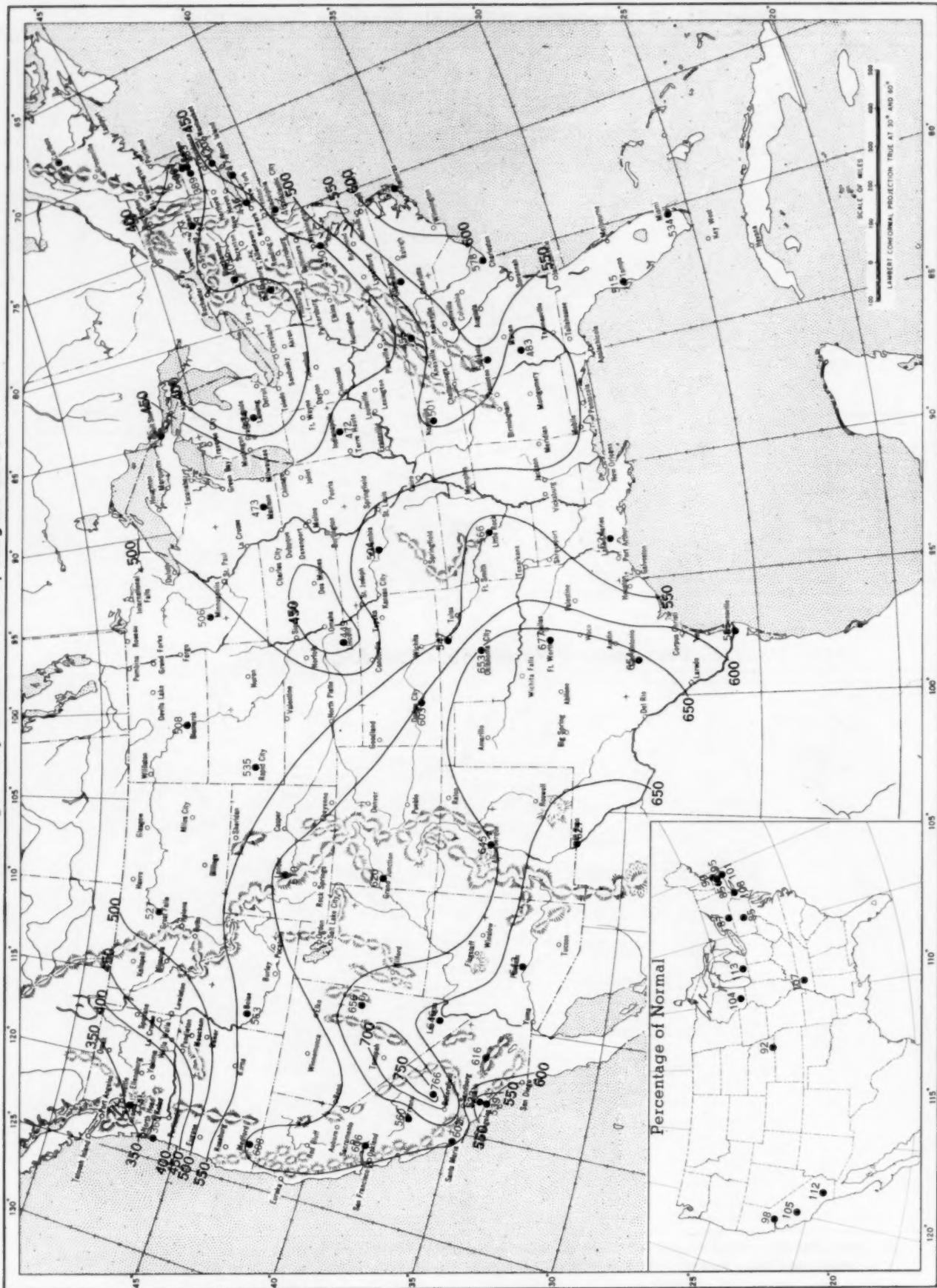
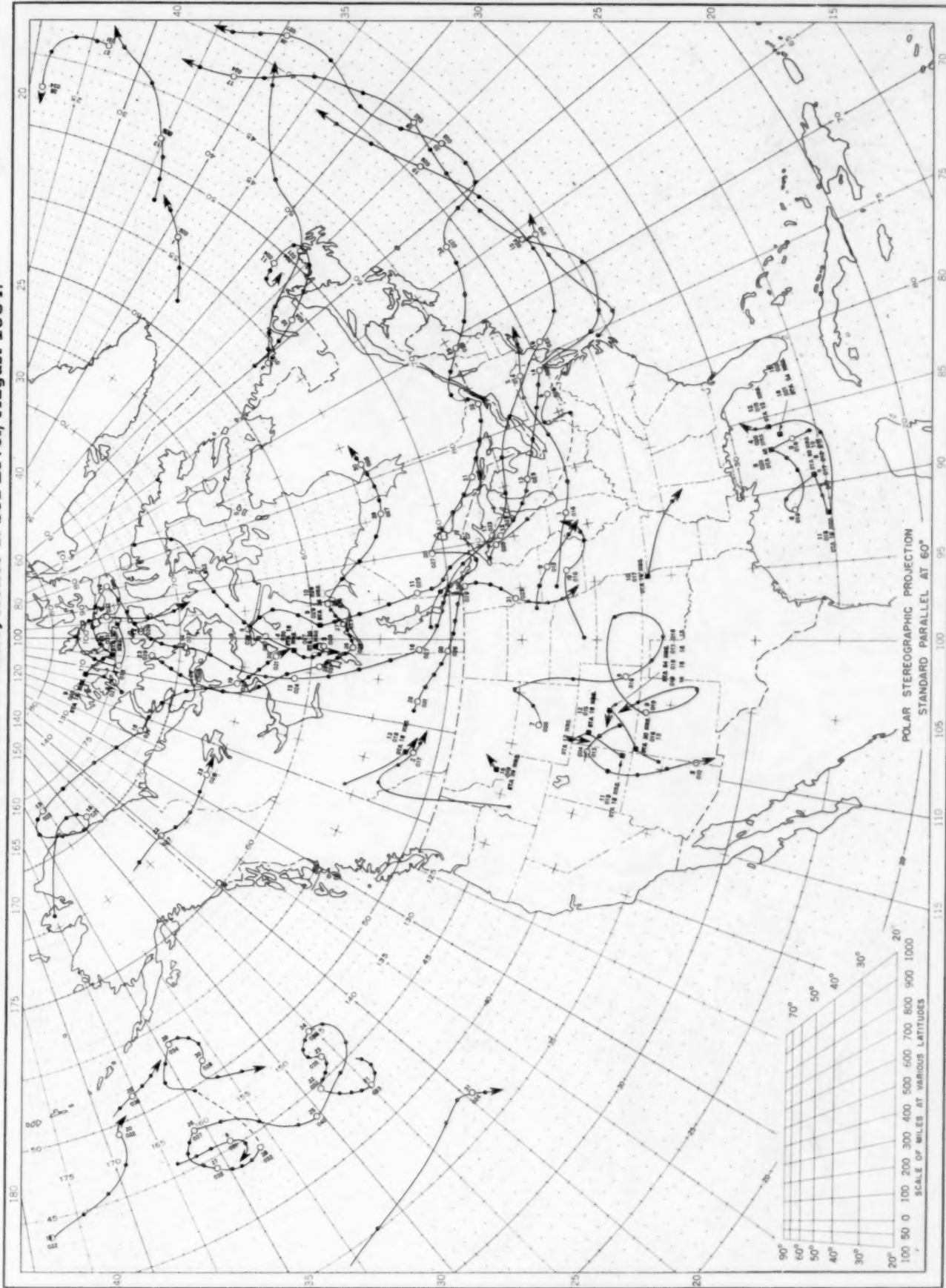


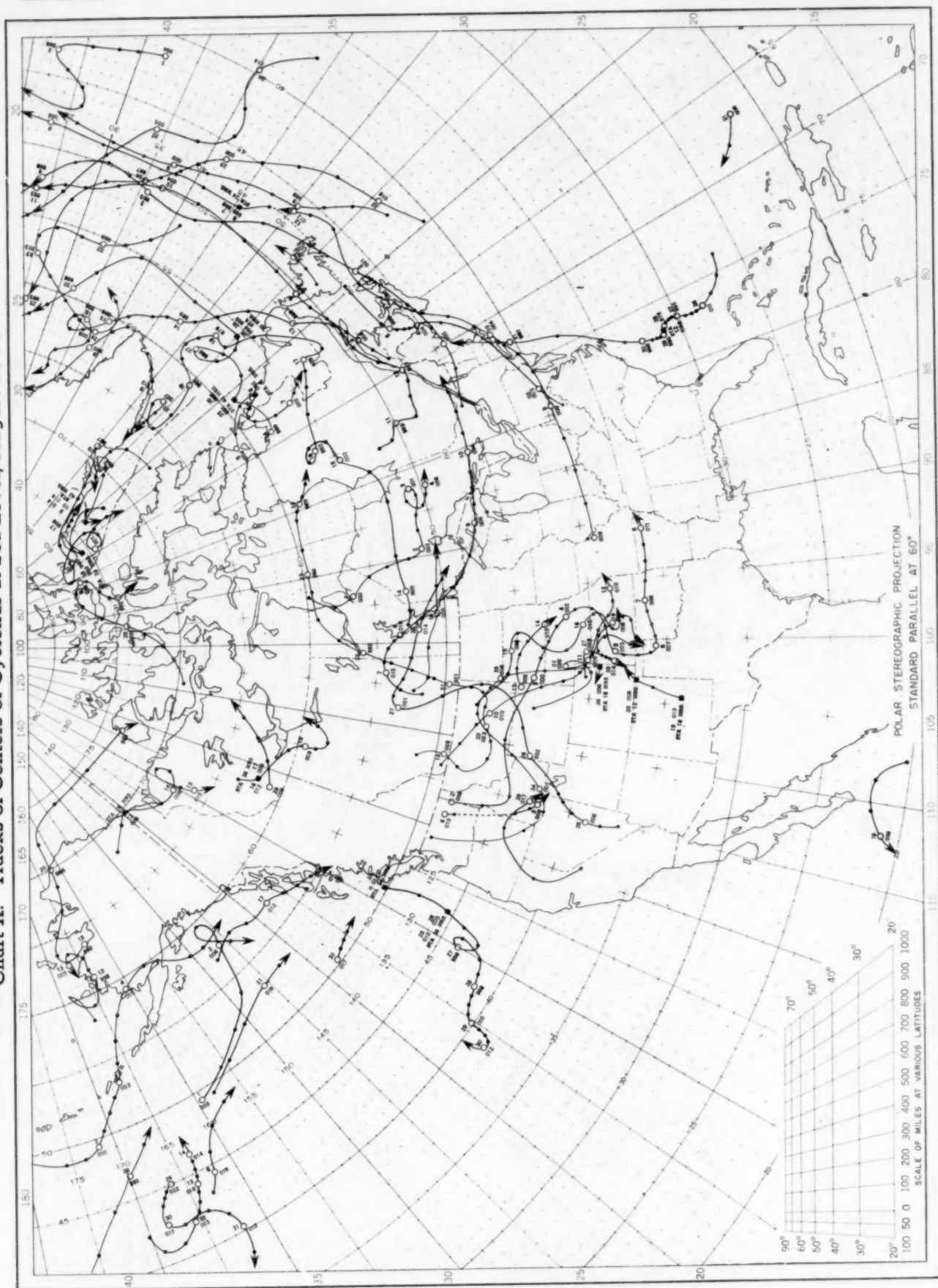
Chart shows mean daily solar radiation, direct + diffuse, received on a horizontal surface in langleys (1 langley = 1 gm. cal. cm.<sup>-2</sup>). Basic data for isolines are shown on chart. Further estimates are obtained from supplementary data for which limits of accuracy are wider than for those data shown. Normals are computed for stations having at least 9 years of record.

Chart IX. Tracks of Centers of Anticyclones at Sea Level, August 1954.



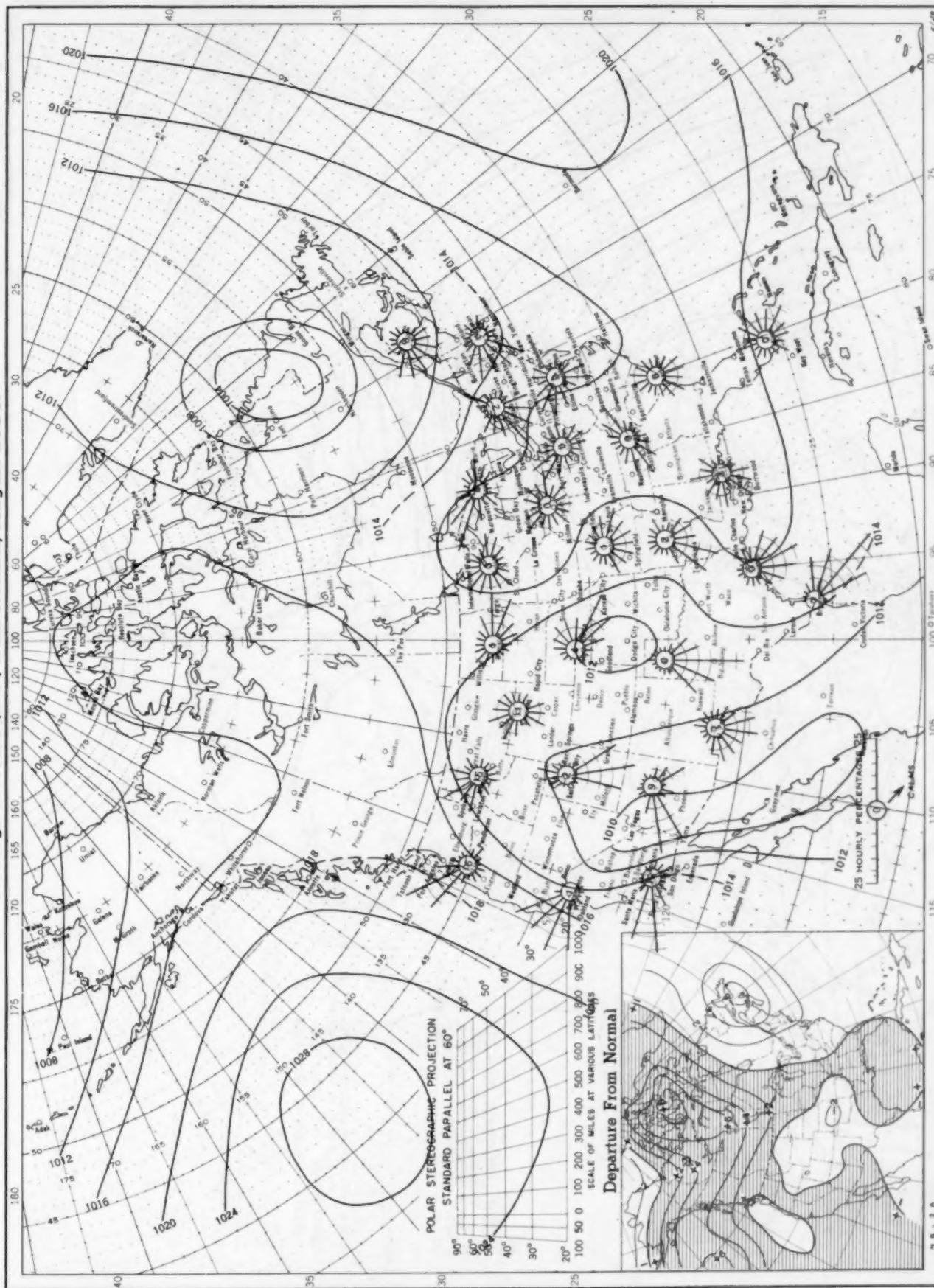
Circle indicates position of center at 7:30 a. m. E. S. T. Figure above circle indicates date, figure below, pressure to nearest millibar.  
 Dots indicate intervening 6-hourly positions. Squares indicate position of stationary center for period shown. Dashed line in track indicates reformation at new position. Only those centers which could be identified for 24 hours or more are included.

Chart X. Tracks of Centers of Cyclones at Sea Level, August 1954.



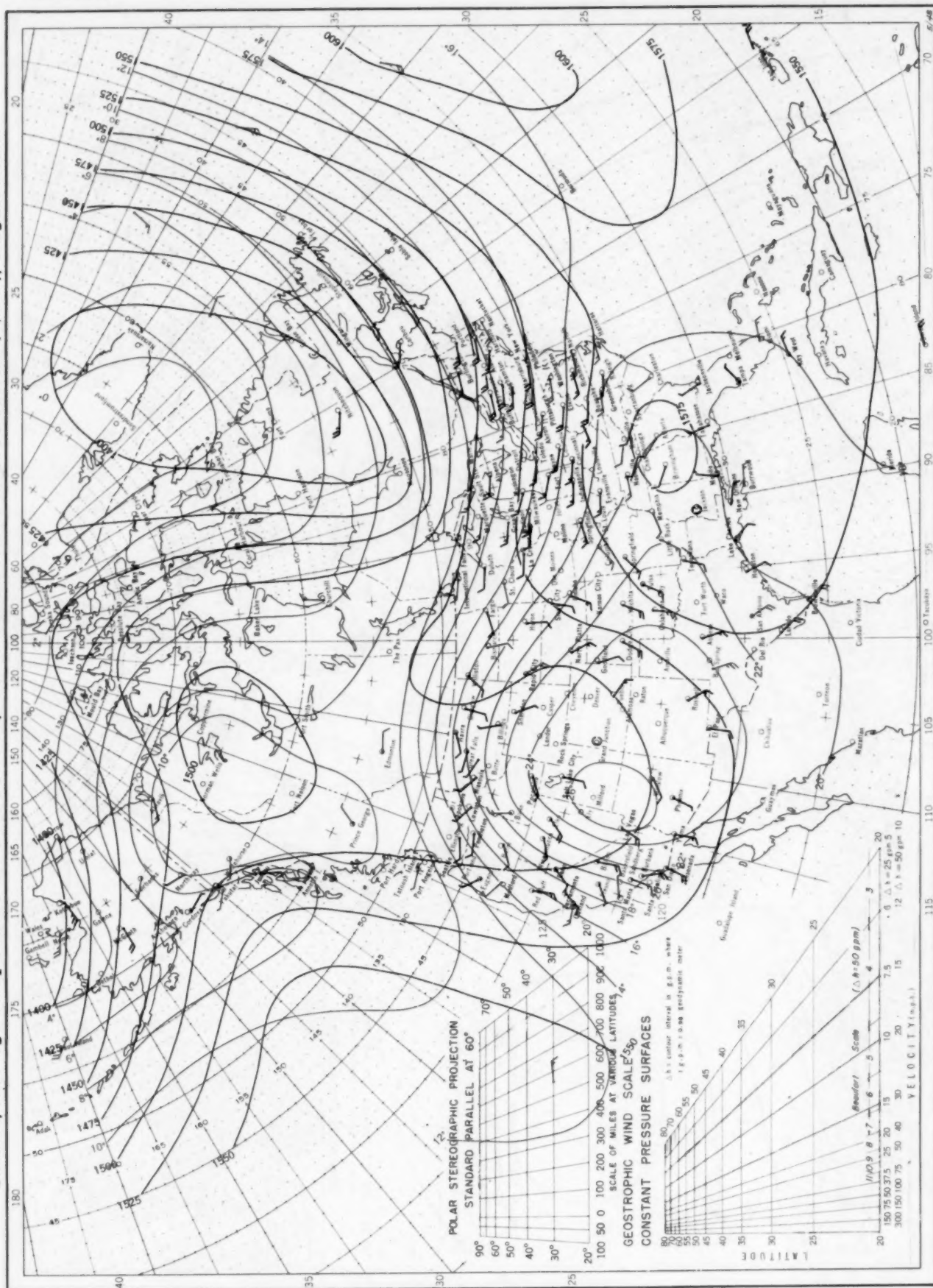
Circle indicates position of center at 7:30 a. m. E. S. T. See Chart IX for explanation of symbols.

Chart XI. Average Sea Level Pressure (mb.) and Surface Windroses, August 1954. Inset: Departure of Average Pressure (mb.) from Normal, August 1954.



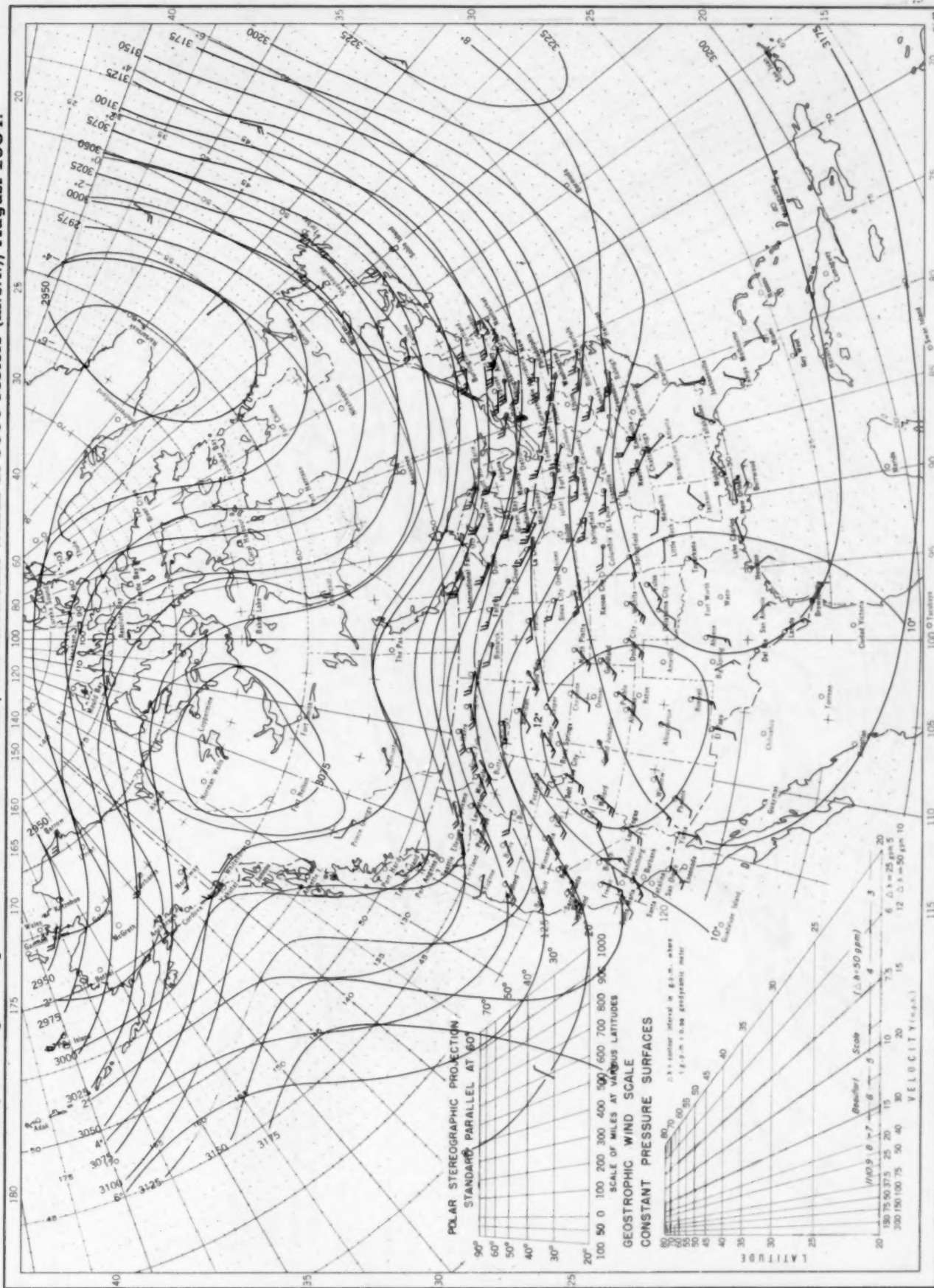
Average sea level pressures are obtained from the averages of the 7:30 a.m. and 7:30 p.m. E.S.T. readings. Windroses show percentage of time wind blew from 16 compass points or was calm during the month. Pressure normals are computed for stations having at least 10 years of record and for 10° inter-sections in a diamond grid based on readings from the Historical Weather Maps (1899-1939) for the 20 years of most complete data coverage prior to 1940.

Chart XII. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 850-mb. Pressure Surface, Average Temperature in °C. at 850 mb., and Resultant Winds at 1500 Meters (m.s.l.), August 1954.



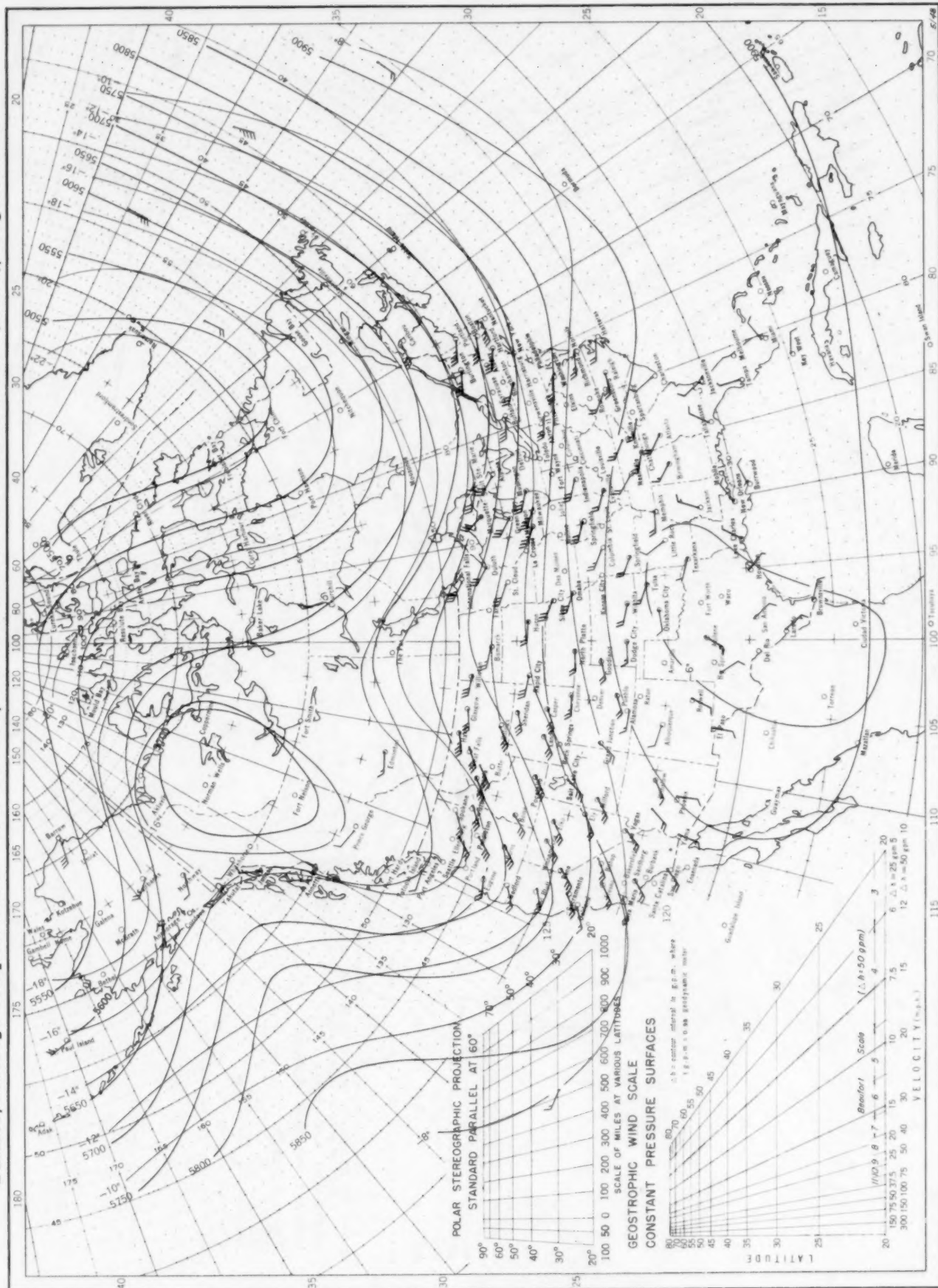
Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0800 G. M. T. Wind barbs indicate wind speed on the Beaufort scale.

Chart XIII. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 700-mb. Pressure Surface, Average Temperature in °C. at 700 mb., and Resultant Winds at 3000 Meters (m.s.l.), August 1954.



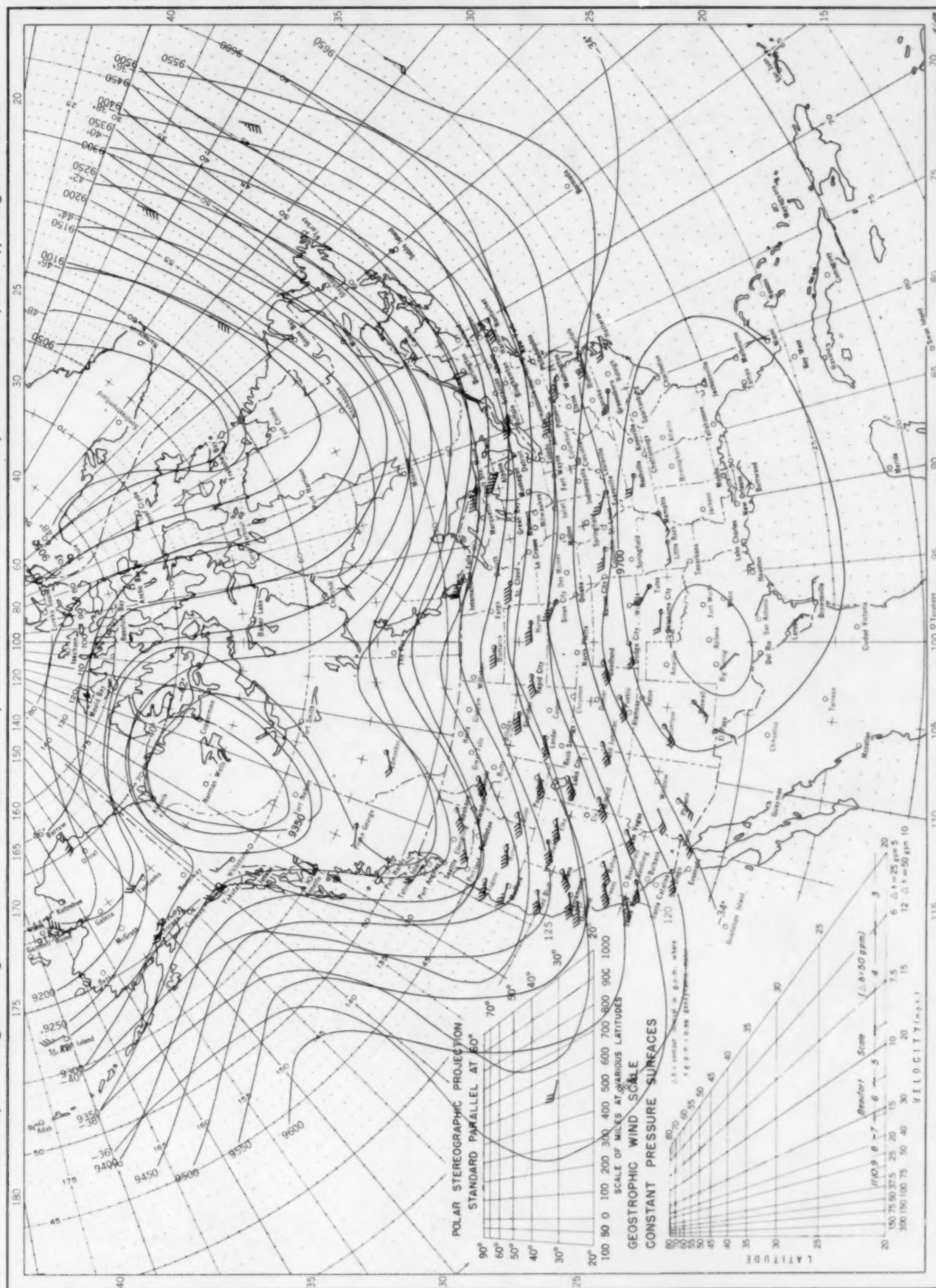
Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T. Wind barbs indicate wind speed on the Beaufort scale.

Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T. Wind barbs indicate wind speed on the Beaufort scale.



those shown in red are based on rawins at 0300 G. M. T. Wind barbs indicate wind speed on the Beaufort scale.

Chart XV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 300-mb. Pressure Surface, Average Temperature in °C. at 300 mb., and Resultant Winds at 10,000 Meters (m.s.l.), August 1954.



Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T. Wind barbs indicate wind speed on the Beaufort scale.